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ATOMIC WEAPONS RESEARCH ESTABLISHMENT

REPORT No. T 49/57

OPERATION BUFFALO

The Radiation Survey of Ground Deposited Radioactivity

J. J Rae

[redacted]

A.W.R.E.,
Aldermaston, Berks.

August, 1957

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United Kingdom Atomic Energy Authority

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REPORT NO. T49/57

OPERATION BUFFALO

The Radiation Survey of Ground Deposited Radioactivity

J. J. Rae

Summary

This report describes the survey of fallout in the test area at Maralinga during Operation Buffalo. The differences between tower and ground detonations are clearly shown and the activity deposited has been deduced for the two cases.

Received on 22nd July, 1957

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1. Introduction

This report describes the methods used to survey the extent of the fallout in the test area from the four atomic explosions, Operation Buffalo, at Maralinga in September and October, 1956.

Rounds 1 and 4 were tower bursts, Round 2 a ground burst and Round 3 an air burst. Detailed surveys were made on Rounds 1 and 2. Round 3 was expected to give little fallout and only readings necessary for the early recovery of scientific records were made.

The Round 4 survey was made by the No. 1 Canadian R.D.U. as a military exercise. The crater surveys on Rounds 1 and 4 were made on D + 10 days by teams of British and Australian army personnel respectively.

2. Survey Area

A grid map of the survey area is shown in Figure 1. The heavy lines are the roads laid by the Task Force prior to the arrival of the Scientific Party. After their arrival it was decided that an accurate radiological survey would be facilitated by sub-divisions of the grid. Secondary tracks were made and are shown as dotted lines in Figure 1. All tracks and roads were mileposted, the milometers of the survey vehicles having been calibrated previously on a chained stretch of road.

3. Vehicles

The vehicles used in the preliminary survey and on the operation itself were hard-topped Landrovers, fitted with 1/10th milometers and two-way radio.

4. Instruments

4.1 Types

Two types of radiation detecting instruments were used:-

(1) γ Survey Equipment Type 1390A.

(2) β/γ Survey Equipment Type 1391A.

4.2 Description

(1) Type 1390A

This battery operated ionisation chamber equipment (Figure 2) has been designed to measure γ dose-rate more accurately than existing radiac survey instruments. The field of view has a solid angle of nearly 4π and response is uniform, to within 8%, over an energy range from 65 keV to 2 MeV. By using two detector units and a common indicator unit the dose-rate scale is covered in ten ranges from 10 mr/h to 30 r/h (full-scale). The ionisation chambers used in both detectors have volumes of about 300 cm^3. The polarising electrode wall thickness is about 450 mg/cm^2 of conducting phenolic plastic which has absorption characteristics very similar to those of air, over the range of γ energies to be measured. The outer shell of the chamber is about 950 mg/cm^2 of aluminium, making a total thickness of about 1400 mg/cm^2. Both ionisation chambers are sealed and filled with dry air at 6.5 atmospheres and at 0.65 atmospheres absolute respectively.

The current from the ionisation chamber is fed into a high value input resistor which is connected in series with the feed-back line of a two valve direct current amplifier. The loop gain of this amplifier without the 100% feedback, is about 40 and the response time obtained on the most sensitive range is less than one second.

(2) Type 1391A

This battery operated equipment was used as the standard β measuring instrument (see Figure 3). It is similar to the 1390A instrument both electrically and mechanically. The ionisation chamber comprises hemispherical collector and polarising electrodes and is covered with a detachable β shield which is removed for β plus γ measurements. The thickness of the β window is 30 mg/cm^2 and that of the shield approximately 1400 mg/cm^2. The ion chamber has a 2π geometry for β radiation.

The dose-rate ranges are 0- 0.1, 0 - 1, 0 - 10 and 0 - 100 r/h and the energy characteristics with the shield on are similar to those of the 1390A equipment.

When in use both 1390A and 1391A instruments were held with the ionisation chamber 1 metre from the operators body and 1 metre from the ground.

5. Round 1 - Method of Survey

5.1 Stages

The survey was made in three stages:-

(1) Initial reconnaissance to enable scientific records to be recovered at an early stage after explosion.

(2) Survey of all main roads and secondary tracks on the grid.

(3) The crater survey.

5.2 Initial Reconnaissance

The survey teams, dressed in full protective clothing, were stationed at Forward Control, 10 miles from Ground Zero, at the time of firing. After briefing, re-entry was made within ten minutes of firing. The object was to confirm that the site previously chosen for the mobile Health Control Centre was clear of fall-out and to erect warning notices at the 2 r/h contour. These dose-rate readings were transmitted to Forward Control enabling an early re-entry programme to commence. Because of the late firing time, 17000 hours, it was not considered advisable to operate the three remaining survey parties and therefore the main survey on the grid did not start until D + 1 day.

5.3 Survey of Roads and Tracks

From D + 1 day to D + 5 days four teams of three surveyors were used. Readings were taken at 1/10th mile intervals and the dose-rates entered on a record sheet together with the location and time of reading. By D + 5 days the survey of all but the central region around Ground Zero had been completed.

5.4 Crater Survey

The crater survey was made on foot on D + 10 days by three teams of two surveyors, readings being taken along three diameters of the crater.

5.5 Dose-Rates

The dose-rate readings converted to H + 24 hours, except those of the crater which are shown in Figure 6, are shown in Figure 4, while Figure 5 shows the "onion" neck of the plume on a larger scale map. The Total Activity readings have been deduced using an observed decay curve for Total Activity (Fission Product + Induced Activity) obtained as a separate task. The corresponding Fission Product dose-rates have been calculated from a theoretical fission product decay curve, Ref. [1].

The crater survey dose-rates given in Figure 6 have been presented as readings actually made on D + 10 days and plotted against distance from Ground Zero. Dust storms and heavy rain occurred during the week after the burst and it was not considered justified to correct the readings back to H + 24 hours.

6. Round 2

As on Round 1 a reconnaissance, by one team, was made of the instrument lane and the Health Control site within 30 min of the explosion. It was also possible for the remaining three teams to make a rapid reconnaissance of the outermost roads of the grid before night-fall and by the same evening it became evident that the fallout had split into two separate plumes, the stem having blown North and the upper part North-Easterly. As in Round 1 dose-rate readings were taken at 1/10th mile intervals on the roads and secondary tracks of the grid. The survey was completed by D + 4 days. The plotting of the North-Easterly plume was complicated as it overlapped the Round 1 pattern, which itself was contributing to the dose-rate. For each position on the grid it was necessary to compute the fraction of the dose-rate contributed by the Round 1 fallout at known positions before the Round 2 fallout pattern could be plotted.

The dose-rates, converted back to H + 24 hours, using the two curves mentioned in Section 5.5, are shown in Figure 7. Figure 8 is a larger scale map showing detail near Ground Zero.

7. Round 3

No detailed survey was made on this round but a rapid reconnaissance to clear the Health Control site, instrument lane and camera towers was made within 2 hours of firing.

Measurements were made at Ground Zero at H + 1 hour and the maximum dose-rate recorded was 17 r/h.

8. Round 4

The survey on this round was made by the No. 1 Canadian RDU, under the Command of Major R. MacDonald, operating under military conditions. An operational headquarters was set up and as the dose-rate readings were made they were radioed to the military commander, converted to the H + 1 hour reading and plotted on a map. The instruments used were Victoreen No. 592 γ Survey Meters and the fallout plot was completed 14 hours after time of burst. The $t^{-1.2}$ decay law was used to convert the dose-rates back to H + 1 hour, but the contour map at Figure 9 has been corrected to H + 24 hours in a similar manner to the previous rounds. Figure 10 is a larger scale map showing detail near Ground Zero.

The crater survey was made on D + 10 days by the Australian RDU and the actual dose-rates measured are plotted against distance from Ground Zero in Figure 11.

9. Rounds 1, 2 and 4 - Integrated Fission Product Deposition

Dale and Bomyer, Ref. [1], have shown that the ratio of dose-rates from fission products (r/h) to fission product deposition level (c/m^2) is 8.75 at H + 24 hours. Curves have been drawn relating fission product deposition

level to the area enclosed by deposition level contours. The area under this curve gives the total deposition within the limits of the grid survey. The curves for Rounds 1, 2 and 4 are shown in Figure 12.

Results:- Round 1 deposition = 5×10^6 curies.

Round 2 deposition = 2.05×10^6 curies.

Round 4 deposition = 4.63×10^6 curies.

10. Discussion

During the survey the dose-rates measured were due to total activity and in drawing the dose-rate contours due to fission products only, it has been assumed in using a ratio between fission products and induced activity that this ratio holds throughout the fallout area. In fact this ratio was measured at a few specific points only and this assumption may not be valid. It has also been assumed that a dose-rate of 8.75 r/h measured at 1 metre above the ground is equivalent to a fission product deposition of 1 c/m^2 of 24 hour fission products and this figure has been used in calculating the total fission product deposition. There is some suggestion that this figure may be too high if applied to rough terrain but no direct evidence is available.

The dose-rates measured in Rounds 1, 2 and 3 are correct to within ± 5% and the positions at which readings were taken known to an accuracy greater than 1/20th of a mile.

Providing the assumptions discussed above are correct the dose-rate contour maps should be accurate to within ± 10%.

The Round 4 survey was made by the No. 1 Canadian RDU using their Victoreen γ survey equipment and it was not possible to investigate the energy response and other characteristics of this equipment. However, independent dose-rate measurements were made along a ten mile stretch of road in the fallout of this round using the 1390A equipment, primarily to check the calibration of special instruments in aircraft which were making an aerial survey. The γ dose-rates obtained with the 1390A equipment were in reasonable agreement with those obtained by the Canadians.

11. Conclusion

The methods of survey proved to be satisfactory. However, any future ground survey work would be facilitated by incorporating compasses in the vehicles and increasing the number of roads in the North-East sector of the survey grid. The accounting of fallout would be increased in accuracy if some experiments could be made to determine the dose-rate above fission products deposited on the local terrain. It so happened that the lowest dose-rates measured in Rounds 1, 2 and 4 were 0.017, 0.008 and 0.01 r/h at H + 24 hours respectively. However, it has been calculated that the error introduced by ignoring lower dose-rates is less than 0.5%. It is felt, therefore, that the reduced deposition on Round 4 is real and cannot be accounted for by experimental error.

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Reference

1. G. C. Dale and Janette C. Bomyer: "Dose Rates from Ground Contaminated with Residual Radioactive Materials from an Atomic Explosion". AWRE Report O-35/56(X).

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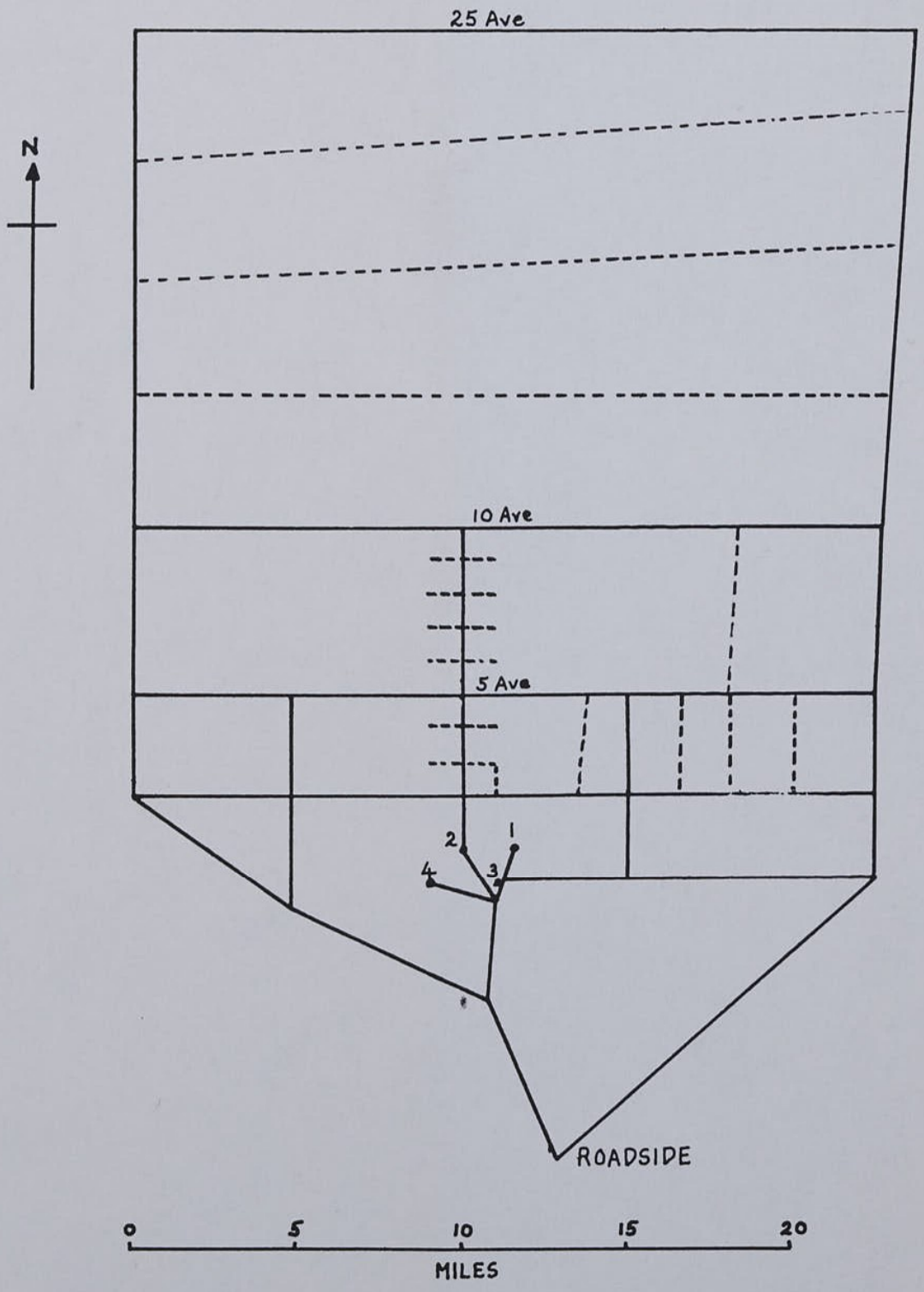


FIGURE 1. GRID LAYOUT MARALINGA.

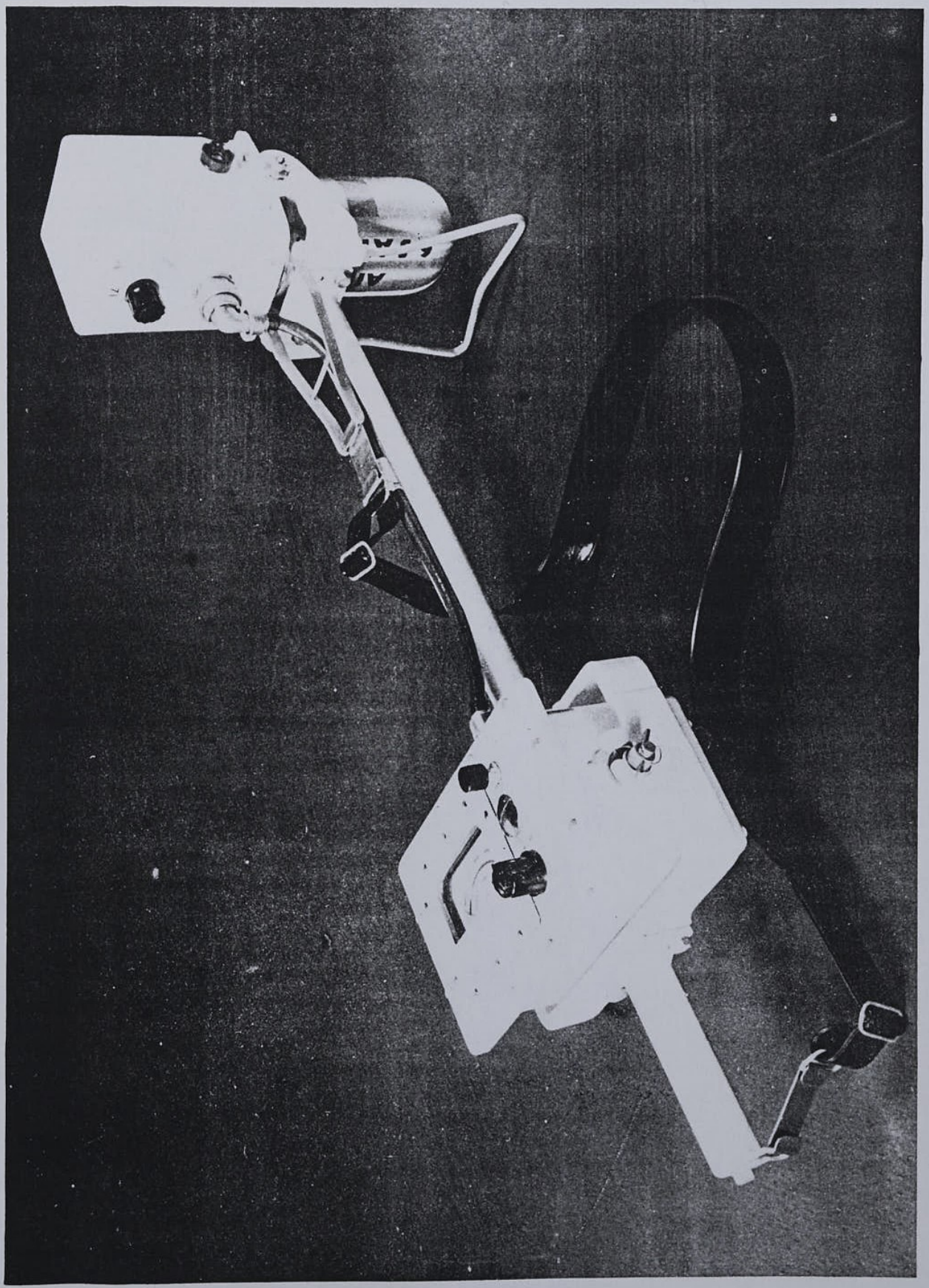


FIG. 2. GAMMA SURVEY EQUIPMENT TYPE 1390A

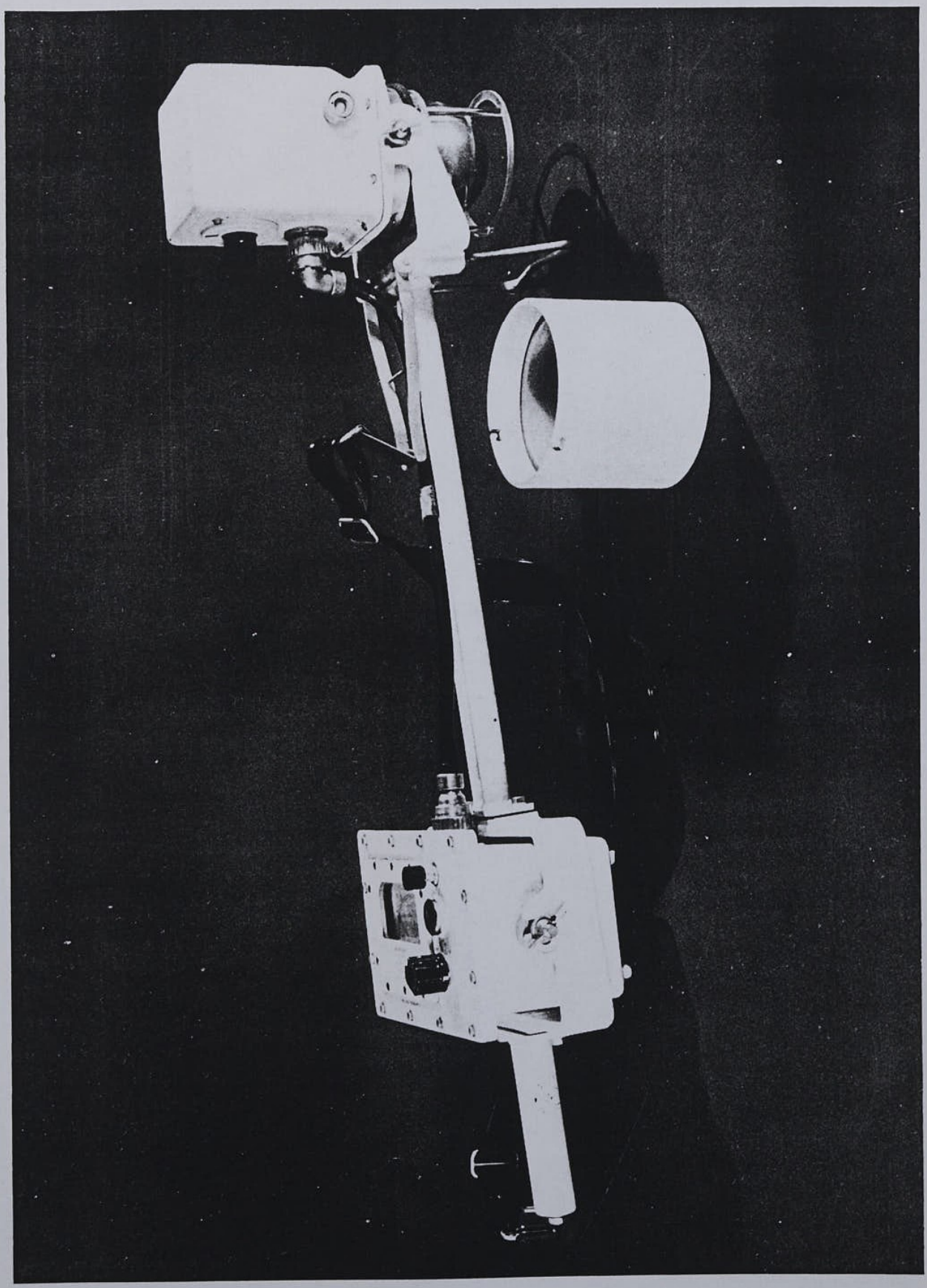
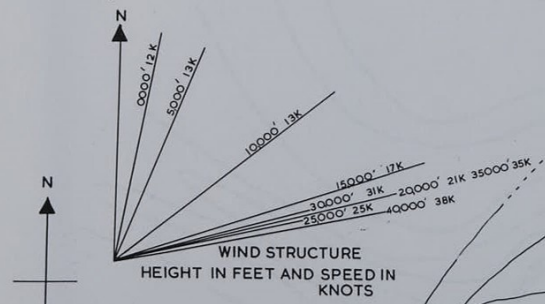


FIG. 3. BETA/GAMMA SURVEY EQUIPMENT TYPE 1391A

EXPLOSION OF 15 K TON (APPROX) WEAPON



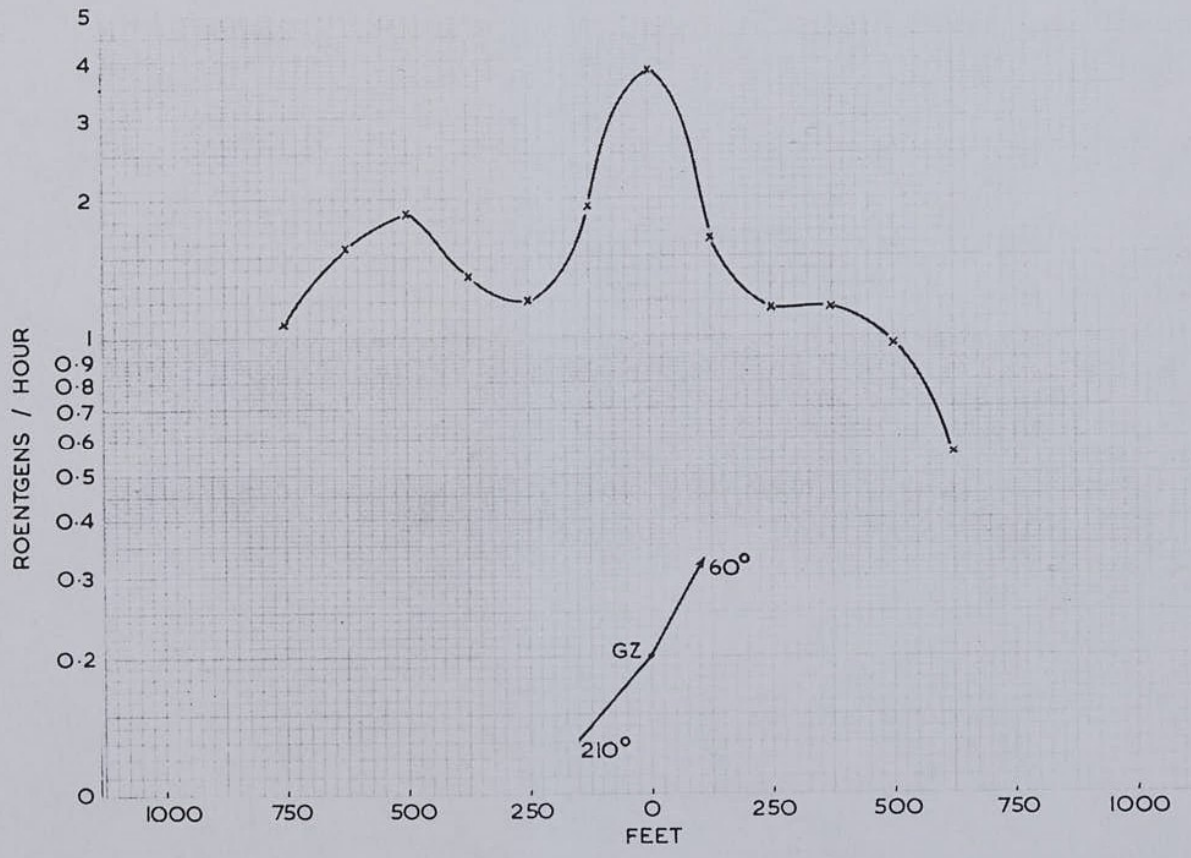
AT H + 24 HOURS

CONTOUR	FISSION PRODUCT DOSE RATE	TOTAL ACTIVITY DOSERATE
A	0·017 r/h	0·022 r/h
B	0·051 r/h	0·067 r/h
C	0·086 r/h	0·113 r/h
D	0·12 r/h	0·158 r/h
E	0·17 r/h	0·224 r/h
F	0·343 r/h	0·451 r/h
G	0·411 r/h	0·540 r/h
H	0·51 r/h	0·671 r/h
J	0·86 r/h	1·13 r/h
K	1·2 r/h	1·58 r/h
L	1·37 r/h	1·8 r/h
M	1·68 r/h	2·21 r/h
N	10·29 r/h	13·53 r/h

CONVERSION FACTOR 1·3

FIGURE 4. BUFFALO ROUND I. GAMMA DOSE RATE CONTOURS.

One Tree



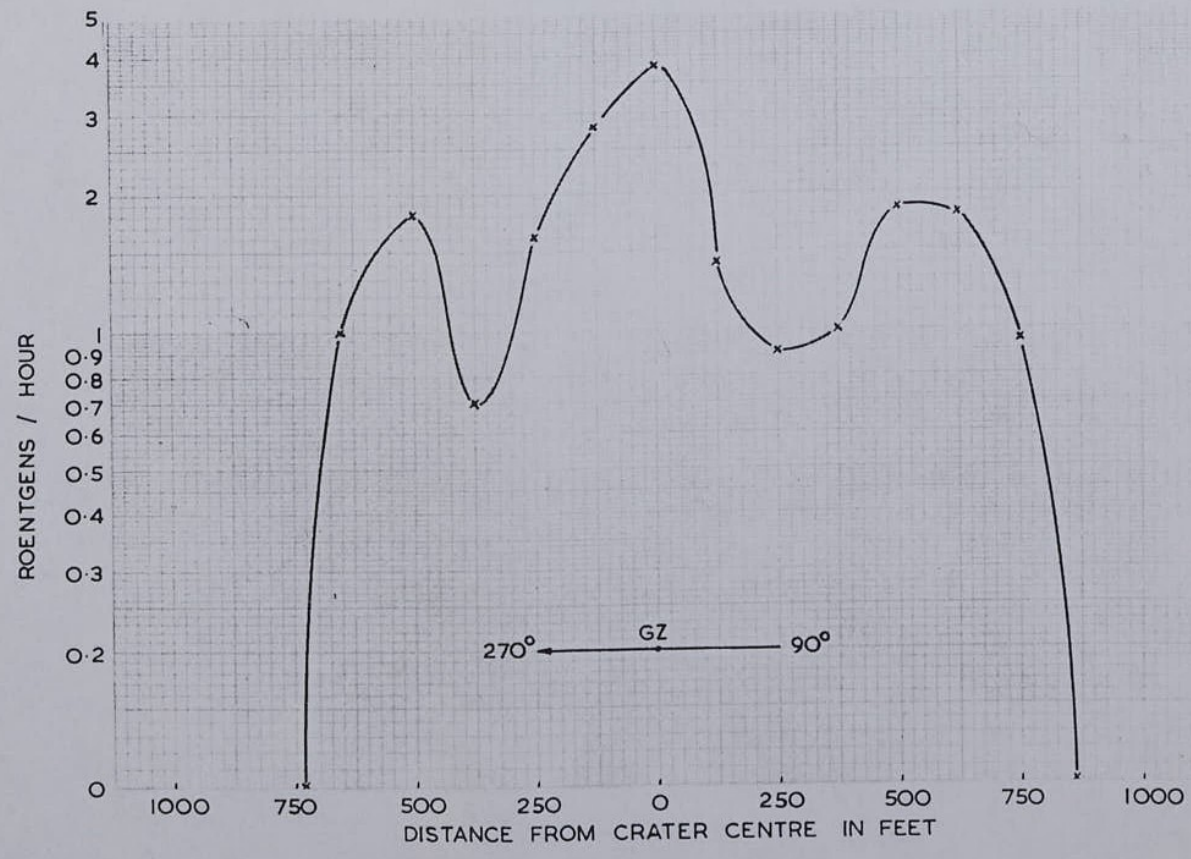


FIGURE 6 BUFFALO ROUND I. CRATER SURVEY GAMMA DOSE RATES

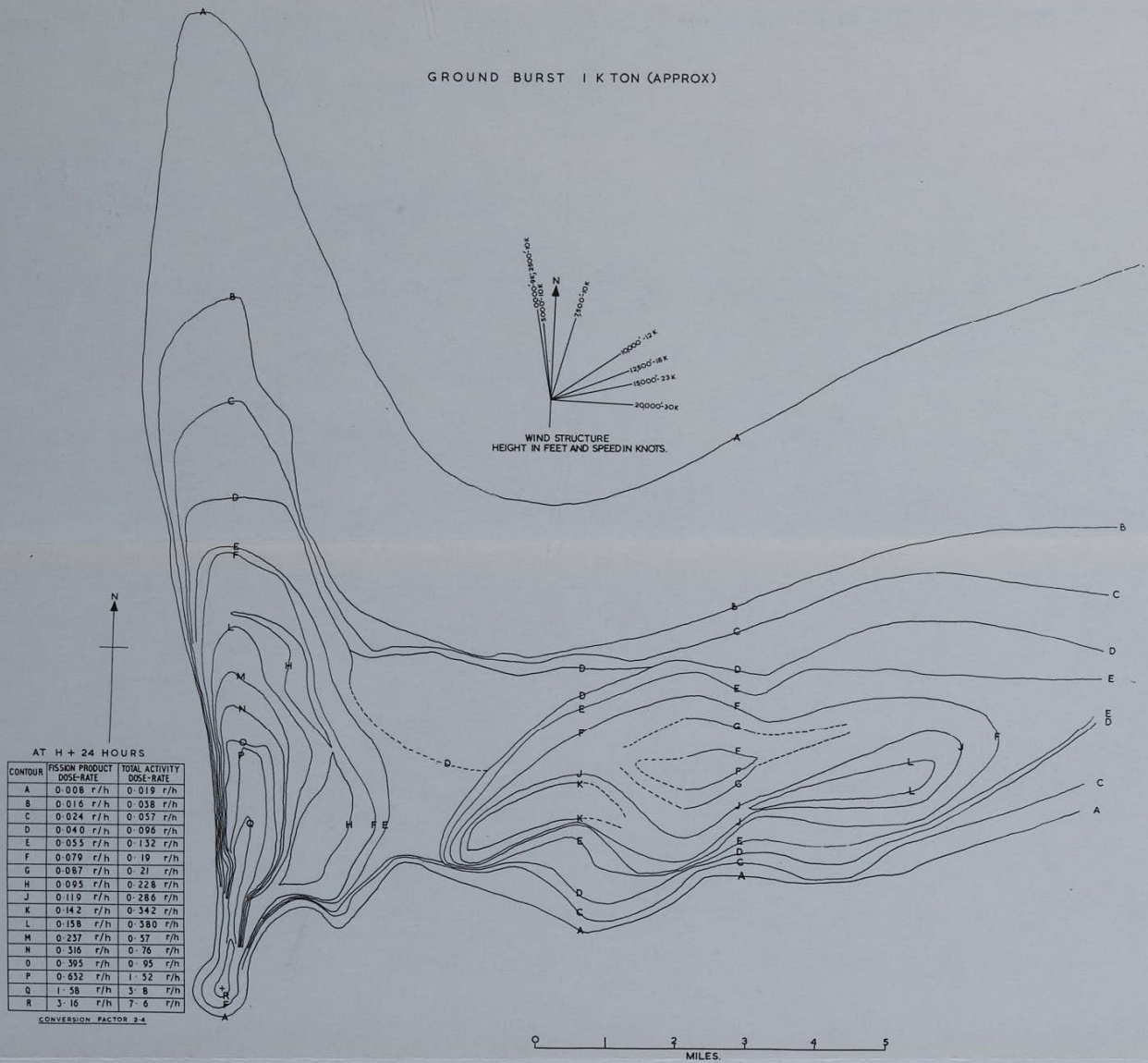
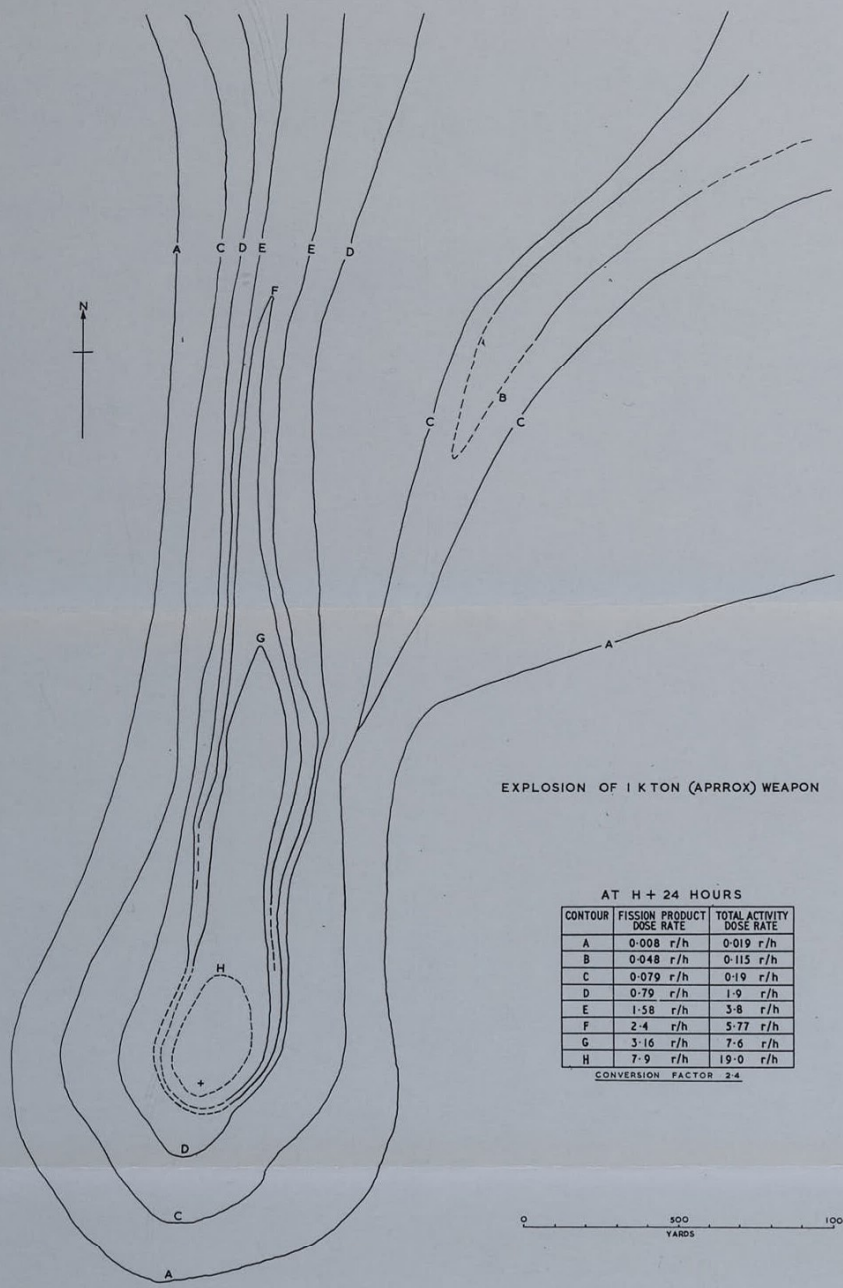


FIGURE 7. BUFFALO ROUND 2. GAMMA DOSE RATE CONTOURS

Marcos



EXPLOSION OF 1 K TON (APRROX) WEAPON

AT H + 24 HOURS

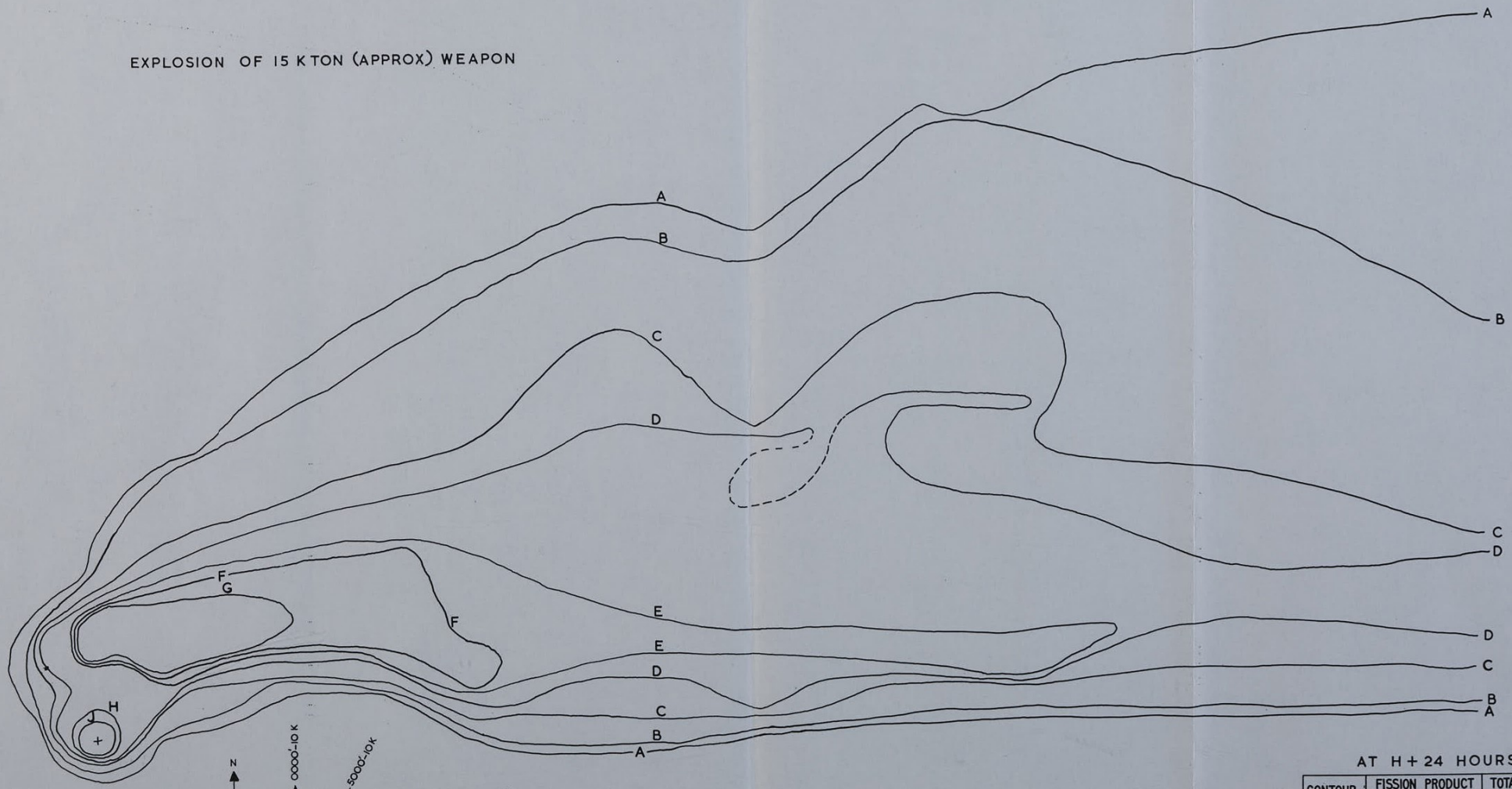
CONTOUR	FISSION PRODUCT DOSE RATE	TOTAL ACTIVITY DOSE RATE
A	0·008 r/h	0·019 r/h
B	0·048 r/h	0·115 r/h
C	0·079 r/h	0·19 r/h
D	0·79 r/h	1·9 r/h
E	1·58 r/h	3·8 r/h
F	2·4 r/h	5·77 r/h
G	3·16 r/h	7·6 r/h
H	7·9 r/h	19·0 r/h

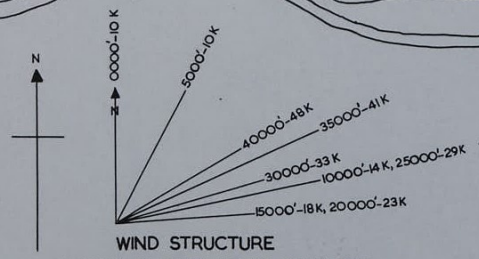
CONVERSION FACTOR 2·4

0 500 1000
YARDS

FIGURE 8. BUFFALO ROUND 2 GAMMA DOSE RATE CONTOURS – CRATER REGION

EXPLOSION OF 15 K TON (APPROX) WEAPON





WIND STRUCTURE
HEIGHT IN FEET. SPEED IN KNOTS.

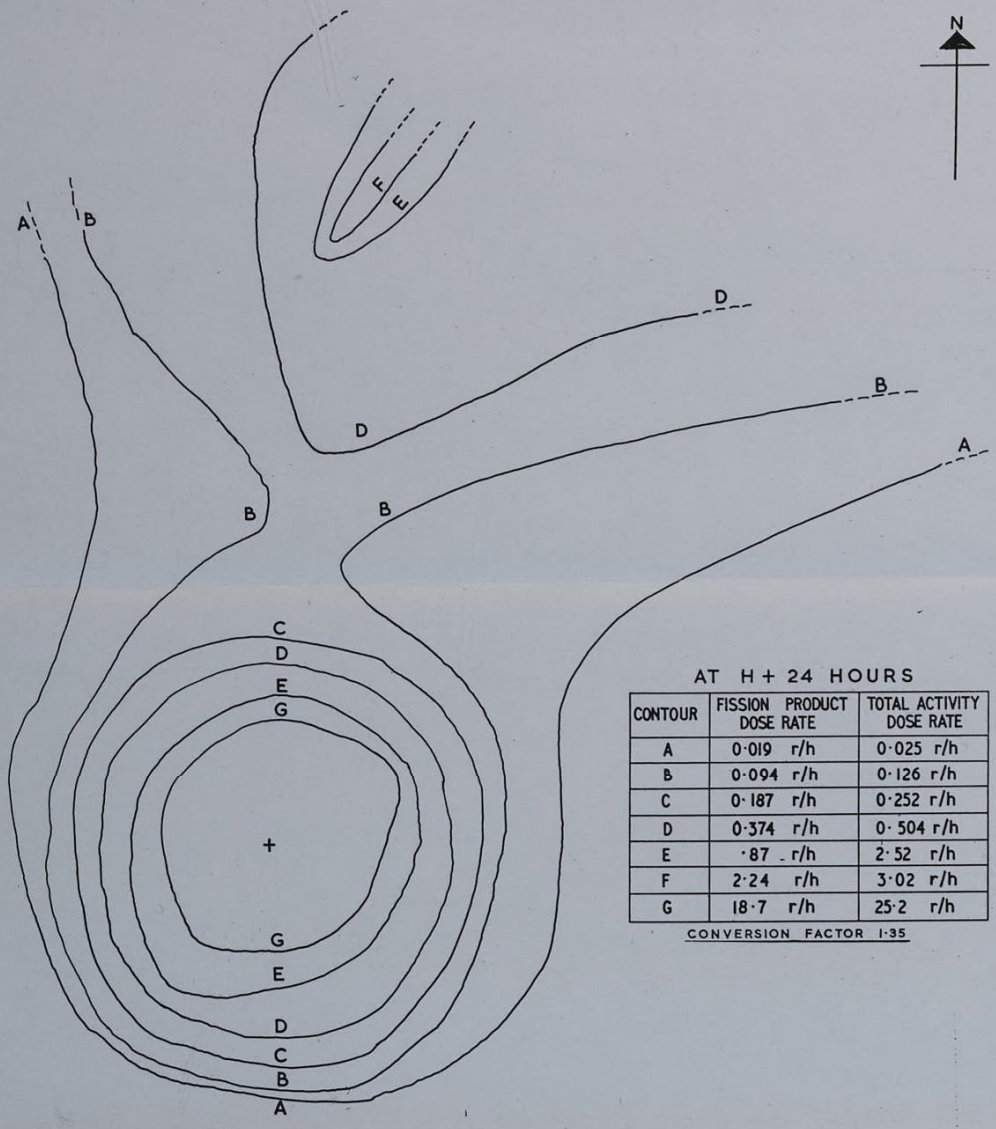
AT H + 24 HOURS

CONTOUR	FISSION PRODUCT DOSE RATE	TOTAL ACTIVITY DOSE RATE
A	0·01 r/h	0·013 r/h
B	0·019 r/h	0·025 r/h
C	0·094 r/h	0·126 r/h
D	0·187 r/h	0·252 r/h
E	0·374 r/h	0·504 r/h
F	0·561 r/h	0·755 r/h
G	0·935 r/h	1·26 r/h
H	5·61 r/h	7·55 r/h
J	18·7 r/h	25·2 r/h

CONVERSION FACTOR 1·35

FIGURE 9 BUFFALO ROUND 4 GAMMA DOSE RATE CONTOURS

Breakaway

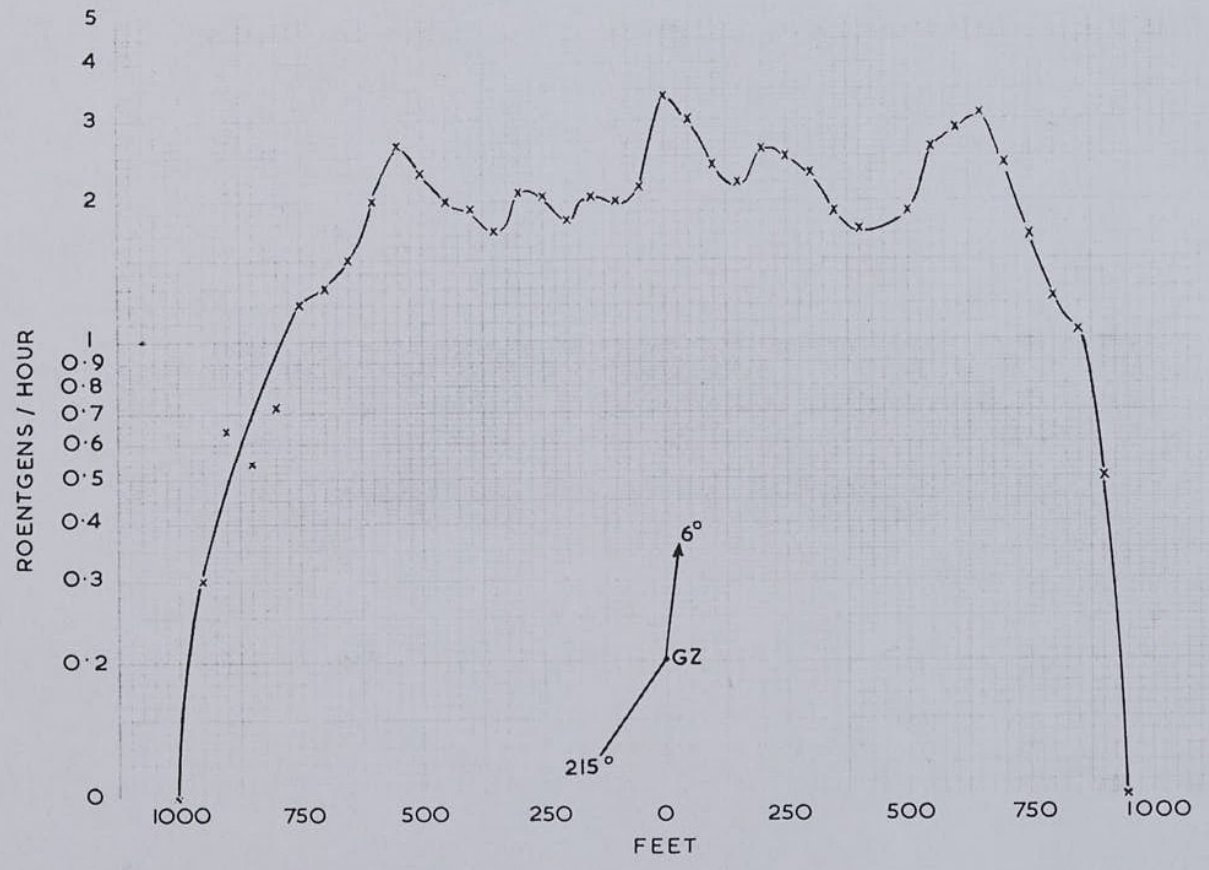


AT H + 24 HOURS

CONTOUR	FISSION PRODUCT DOSE RATE	TOTAL ACTIVITY DOSE RATE
A	0·019 r/h	0·025 r/h
B	0·094 r/h	0·126 r/h
C	0·187 r/h	0·252 r/h
D	0·374 r/h	0·504 r/h
E	·87 r/h	2·52 r/h
F	2·24 r/h	3·02 r/h
G	18·7 r/h	25·2 r/h

CONVERSION FACTOR 1·35

FIGURE 10. BUFFALO ROUND 4 GAMMA DOSE RATE CONTOURS – CRATER REGION



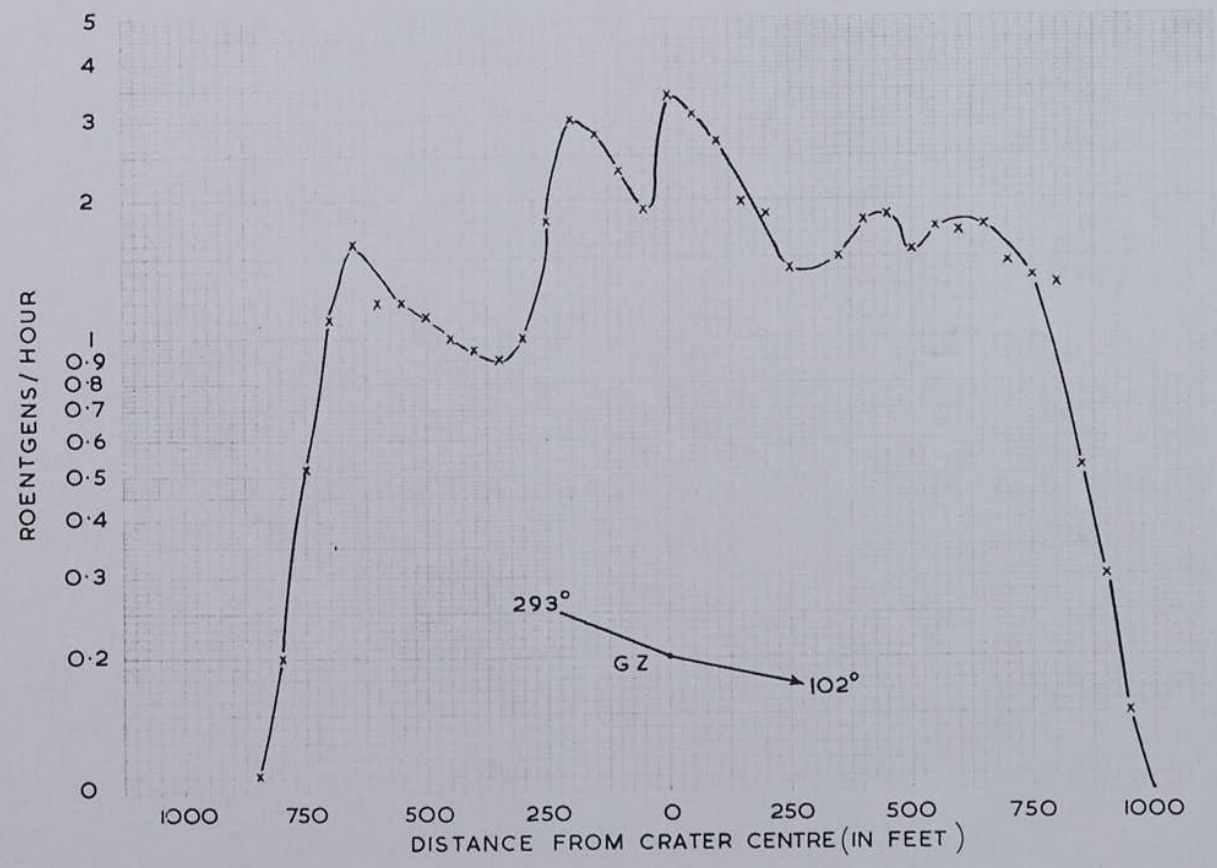


FIGURE 11 BUFFALO ROUND 4. CRATER SURVEY GAMMA DOSE RATES

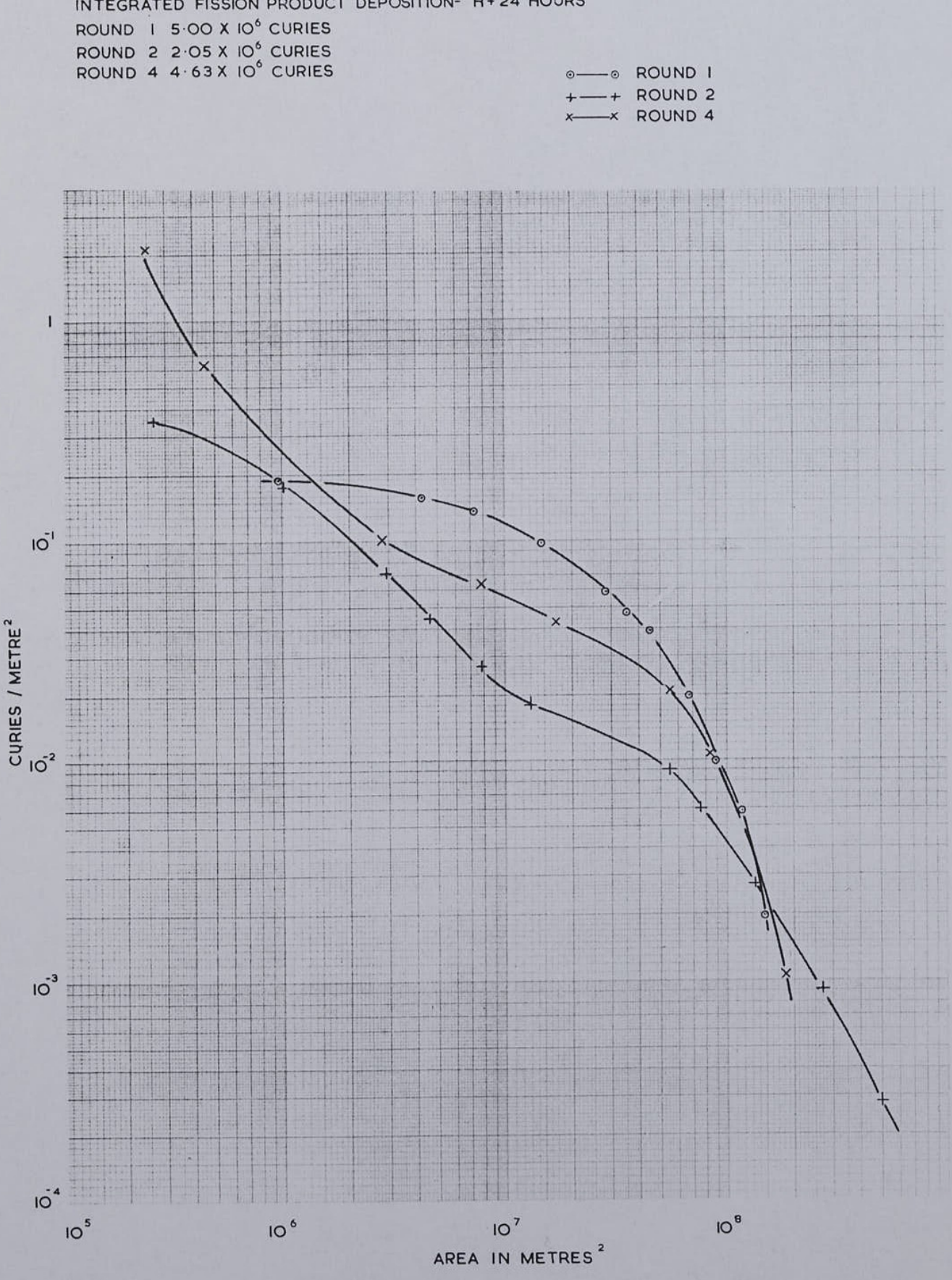


FIGURE 12 ROUNDS 1, 2, & 4. INTEGRATED FISSION PRODUCT DEPOSITION – H+24 HOURS

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UNITED KINGDOM ATOMIC ENERGY AUTHORITY

ATOMIC WEAPONS RESEARCH ESTABLISHMENT

REPORT No. T 9/55

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OPERATION TOTEM

Radiation Surveys of Totem Craters

J. J. Rae

A.W.R.E.,
Aldermaston. Berks.

October, 1955.

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ATOMIC WEAPONS RESEARCH ESTABLISHMENT

REPORT T9/55

Radiation Surveys of Totem Craters

J. J. Rae

Summary

The craters of the two Totem weapons were re-visited after 630 days and a careful survey made of the residual activity. At the same time soil and vegetation samples were collected.

The results of the survey are compared with those made at D + 9 days.

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1. Introduction

Two atomic devices code named Totem 1 and Totem 2 both of similar yield were exploded at EMU Flats South Australia on 15th October and 27th October 1953 respectively. The testing site was revisited in July 1955 and this report describes the methods used and the results obtained during a radiological survey of the crater areas. Discrepancies between the dose rates now measured and those calculated from dose decay curves based on dose rate measurements over a period from H + 1 hour to D + 40 days are discussed.

A brief description is also given of the methods used to collect soil and vegetation samples for analysis.

2. It was decided that the most practical method of making the survey would be to take readings at five-pace intervals along eight symmetrically spaced radii of a circle the centre of which would be ground zero. Ground zero (O) in each crater was fixed accurately between the four square base plates of the original towers and white posts were erected from which compass bearings could be made. The compass bearing of the line of iron posts in the old instrument lanes was taken as a zero line OA and from the centre it was possible to direct the erection of seven more white posts B, C, D, E, F, G and H at 45° intervals in a clockwise direction and at about 200 yds radius from O.

3. Two types of instruments were used in the survey:

(a) a modified 1043 D gamma monitor with a 6.7 inches x 9 inches diameter Tufnol chamber of wall thickness 1,600 mg per cm^2, sufficient to absorb primary beta radiation. The instrument thus modified read 0-16 mr per hour. The response of this instrument against photon energy is shown in Fig. 3.1.

(b) a 1313 gamma monitor which read 0-50, 0-500, 0-5000 mr per hour respectively on three ranges.

Both these instruments were carefully calibrated against a known Cobalt 60 source at Aldermaston. They were checked in the field on the day preceding the survey and found to have held their calibration.

4. Protective clothing consisting of white boiler suits, socks, rubber boots cloth overshoes, linen caps and rubber gloves was worn by all working in the crater area. It was not considered necessary to wear respirators as no dust appeared to be thrown up from the "pie-crust" surface of the ground.

5. The 1043D monitor was regarded as the most reliable and accurate instrument and its range 0-16 mr per hour was sufficient for recording the dose rate at all points except for an area 10 feet in diameter at the centre of Totem 1. A comparison was made between the 1043 and 1313 monitors over a reduced area 60 yards diameter at the centre of each crater. This showed that the 1313 monitor was reading 25% high possibly due to inadequate shielding of this instrument to Beta radiation. All survey measurements were taken with the instrument at armslength and 1 metre from the ground.

6. Figs 6.1 - 6.4 show the dose rate measurements from the fringe of the crater to ground zero.

The maximum dose rates recorded in this systematic survey occurred at ground zero in each case and were as follows:

Totem 1 - 18.5 mr per hour

Totem 2 - 16 mr per hour

7. As a matter of interest spot checks were made on numerous pieces of loose metal, e.g. girders, gear wheels, electric motors, which were scattered indiscriminately in both crater areas and were presumably part of the original towers. Readings were made both close to the surface of these specimens and at 1 metre distant using a 1313 monitor and several readings in mr per hour are tabulated below.

Crater	Near Surface	1 metre distant	
T1	29	15	
T1	80	20	
T1	60	21.5	
T1	120	21	
T1	700	38.5	18" square plate 25 yards in general direction OE
T1	70	10	
T2	70	10	
T2	600	75	Gear wheel 3 ft. diameter between OD and OE, 45 yards from the centre
T2	100	32	One of the four square tower base plates.

The above figures were obtained off purely random samples of debris, and it is interesting that from only one of the tower base plates was a high reading obtained, the others showing no significant increase over the surrounding level.

8. To obtain a representative sample of crater soil an area 2 metres square was marked out on a reasonable flat part of the crater of Totem 1 and the surface layer of earth collected. Improvised containers were made out of two galvanized iron dustbins no other clean containers being available. For this operation full protective clothing including respirators was worn and care was taken to seal and wire down the bin lids to prevent the spread of radioactive dust. Thus dose reading at 1 metre above the sample area just before collection was 11.5 mr per hour and the distance and direction of the sample area from the centre was 8 yds. along OH. The total weight of earth collected was about 400 pounds.

Smaller samples of vegetation and soil, both surface and 5" deep were collected at known intervals up to 8 miles down the fall-out area of Totem 1. Owing to the terrain it was not possible to collect as many samples of grass as was hoped, but representative samples of herbage and soil were collected and packed in polythene bags.

9. Previous surveys of these two craters had been made on D + 9 days. Comparisons on an arbitrary scale, of measurements made along the same diameter are shown in Figs 9.1 and 9.2.

Using the measured decay factor up to 40 days, together with a theoretical decay to 630 days, which agreed with the Totem decay up to 40 days and with the Hurricane up to 400 days, the centre values at H + 1 hour and D + 630 days have been evaluated and are shown below:-

Crater	H + 1 Calculated	D + 9 Measured	D + 630 Calculated	D + 630 Measured
Totem 1	4400 r/hr	5.3 r/hr	11 mr/hr	18.5 mr/hr
Totem 2	7750 r/hr	9.3 r/hr	19 mr/hr	16.0 mr/hr

It will be seen that the overall decay is in good general agreement with theory, but it is interesting to note that whilst Totem 2 had a much higher activity originally it is now somewhat lower. Although Fe 59 is undoubtedly present in the crater area this reversal of dose-rates cannot be attributed solely to the addition of this isotope to the normal fission product distribution.

[redacted]

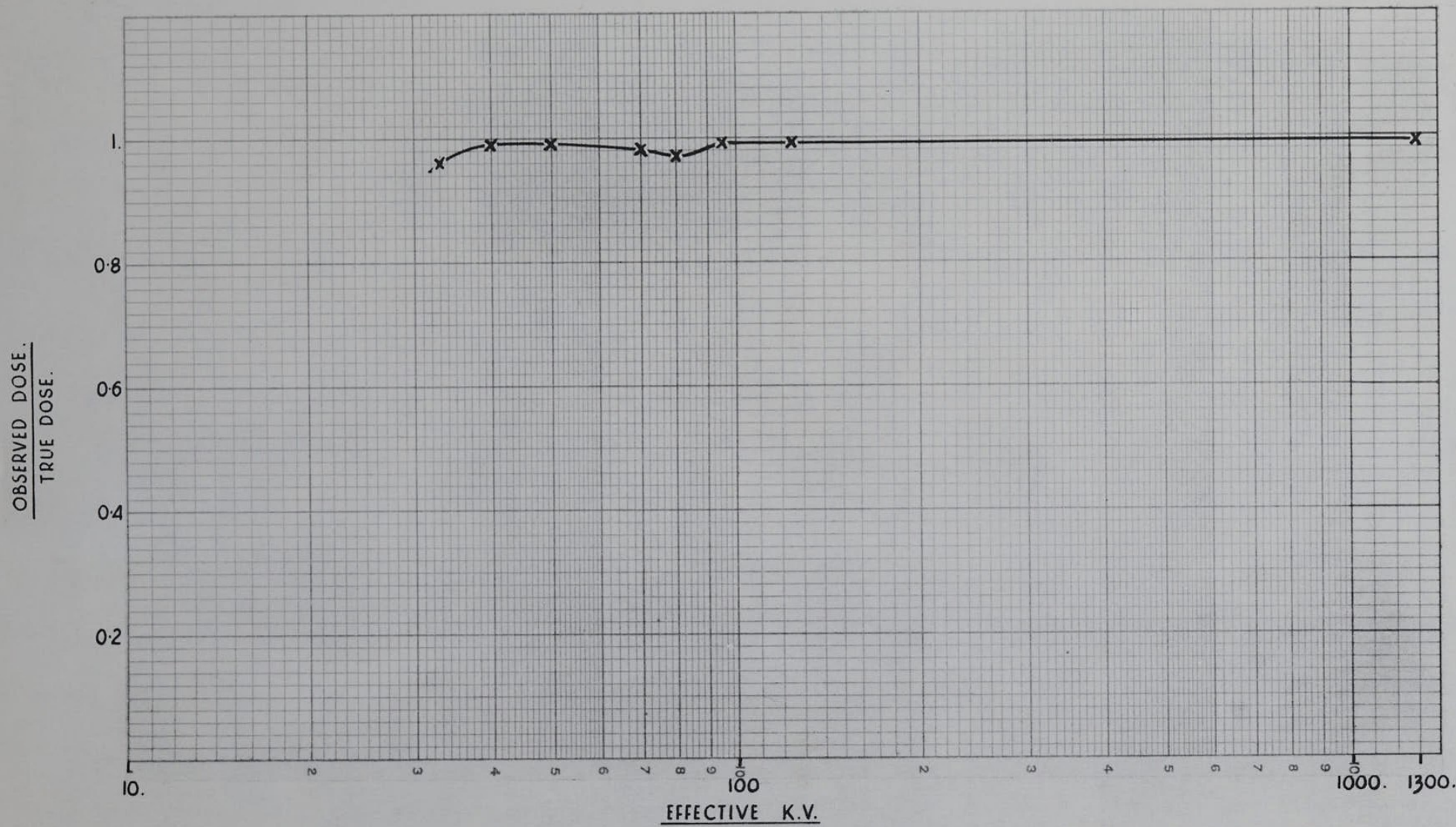

FIG. 3·1. ENERGY RESPONSE OF MODIFIED 1043D.

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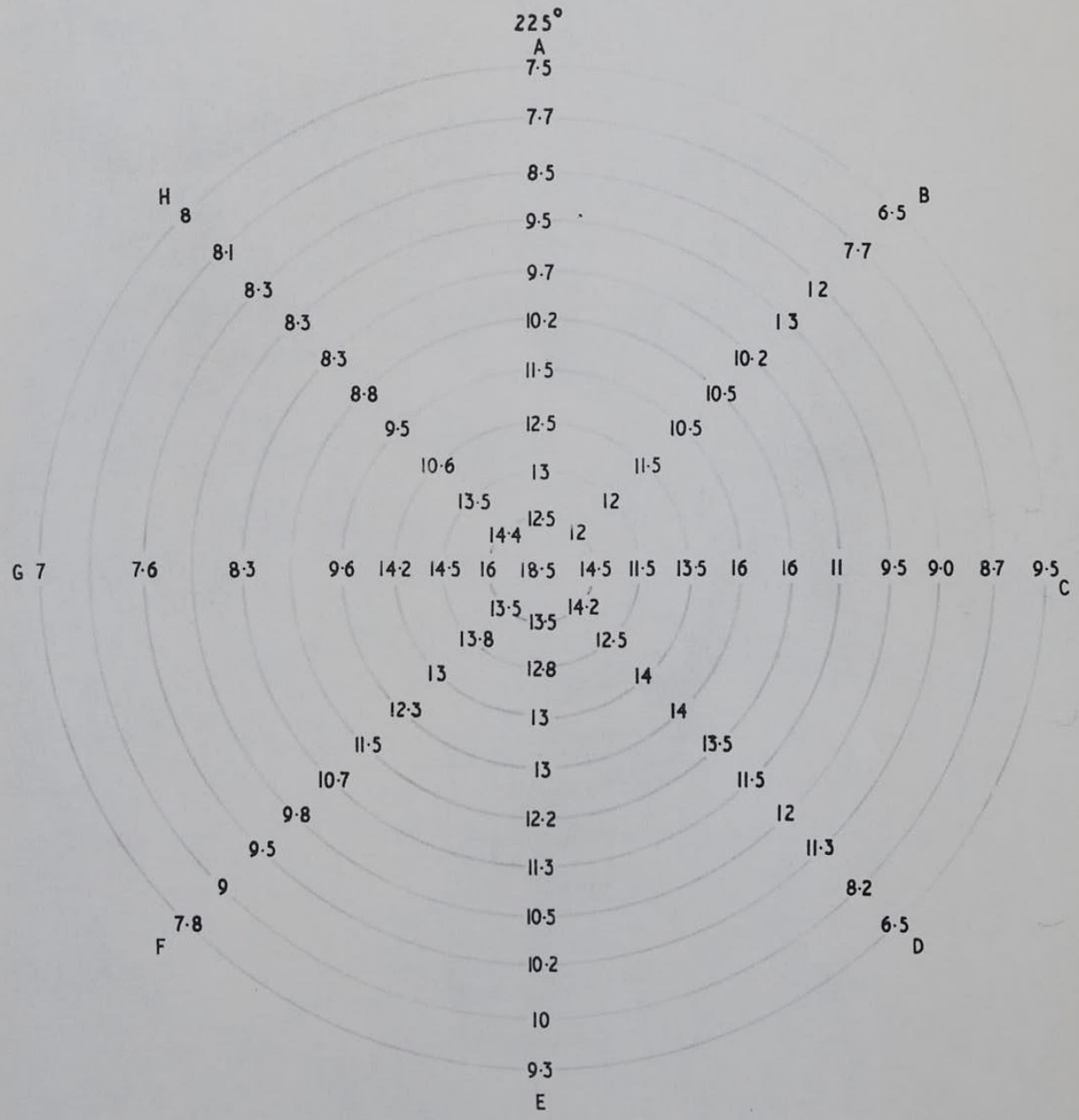

EACH CIRCLE REPRESENTS 5 PACES = 11 FEET.

FIG.6·1. DOSE RATE IN MILLIRONTGENS PER HOUR IN T.I. CRATER ON 5th JULY 1955.

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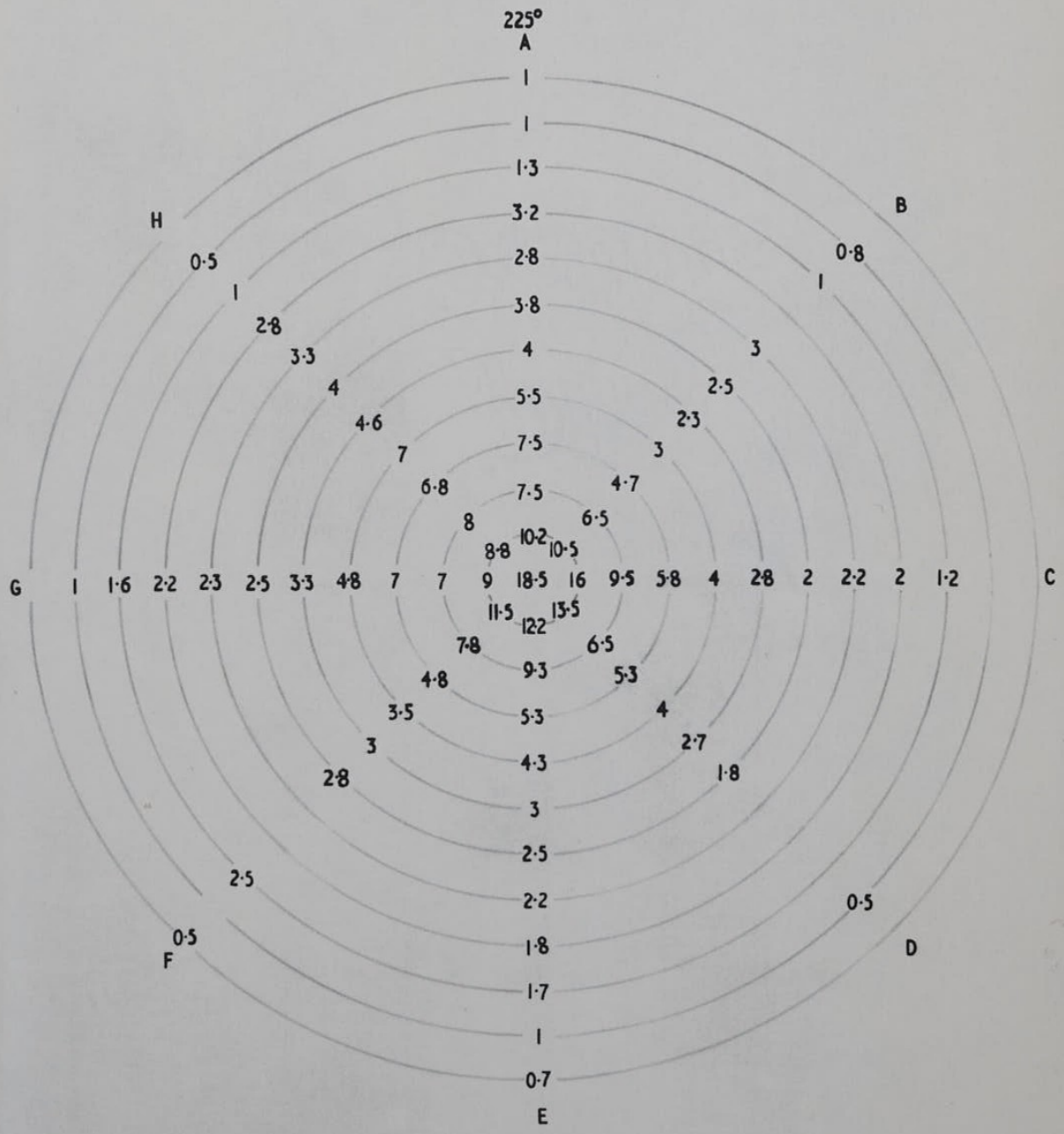

EACH CIRCLE REPRESENTS 25 PACES = 55 FEET

FIG 6·2 DOSE RATE IN MILLIRONTGENS PER HOUR IN T.I. CRATER ON 5th JULY 1955.

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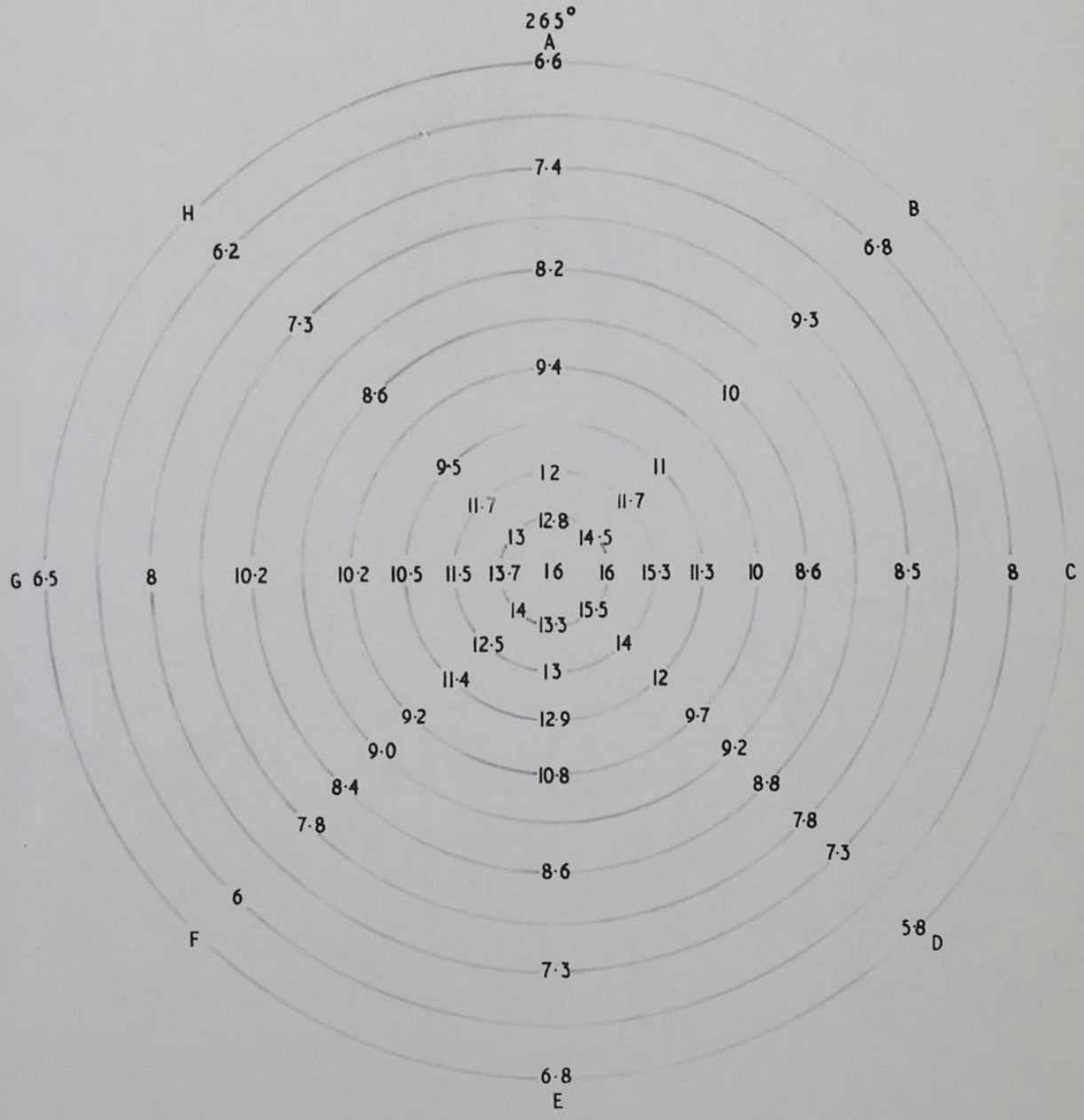

EACH CIRCLE REPRESENTS 5 PACES = 11 FEET.

FIG. 6·3. DOSE RATE IN MILLIRONTGENS PER HOUR IN T. 2. CRATER ON 6th JULY 1955.

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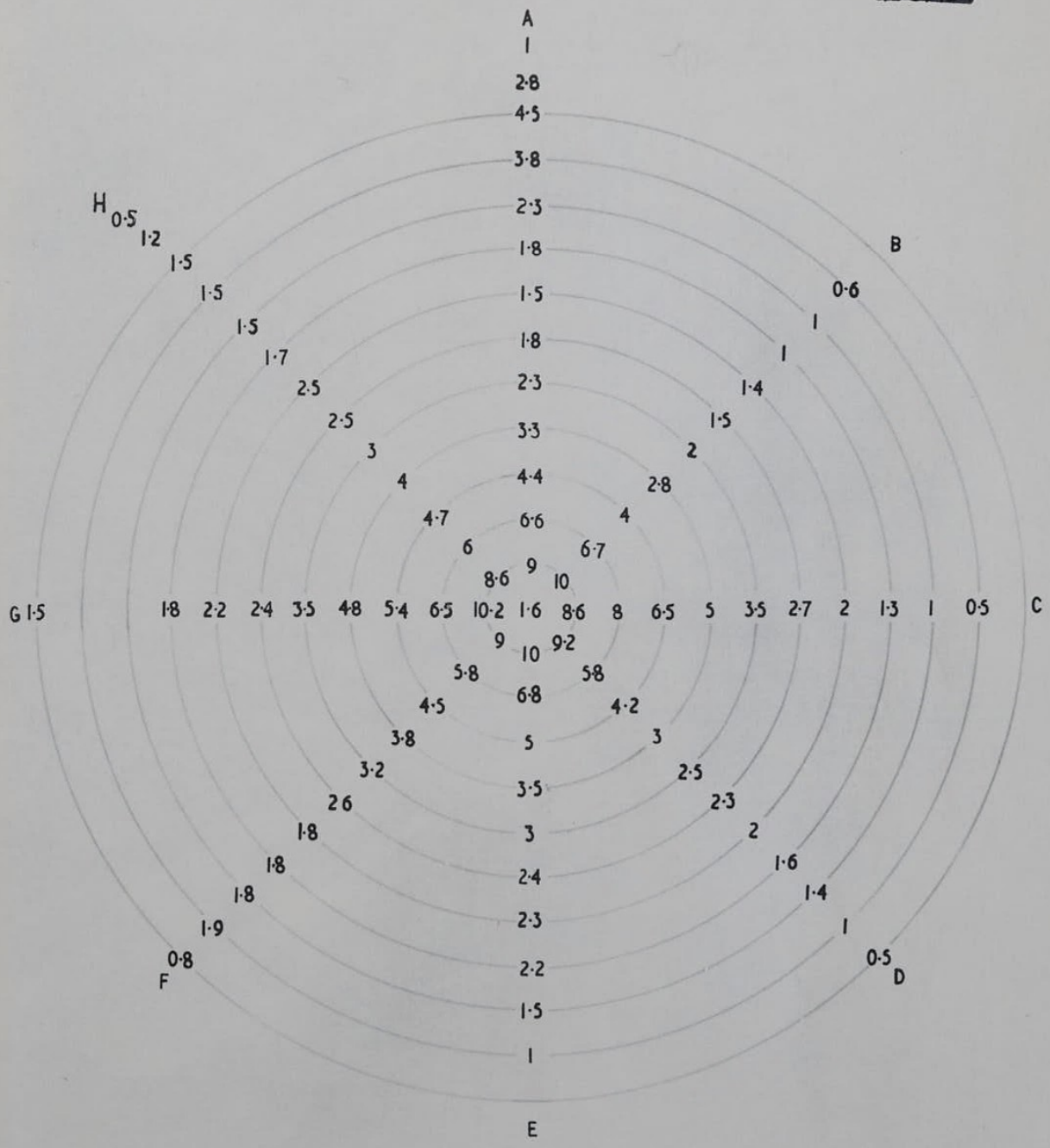

EACH CIRCLE REPRESENTS 25 PACES = 55 FEET

FIG. 6·4 DOSE RATE IN MILLIRONTGENS PER HOUR IN T. 2. CRATER ON 6th JULY 1955.

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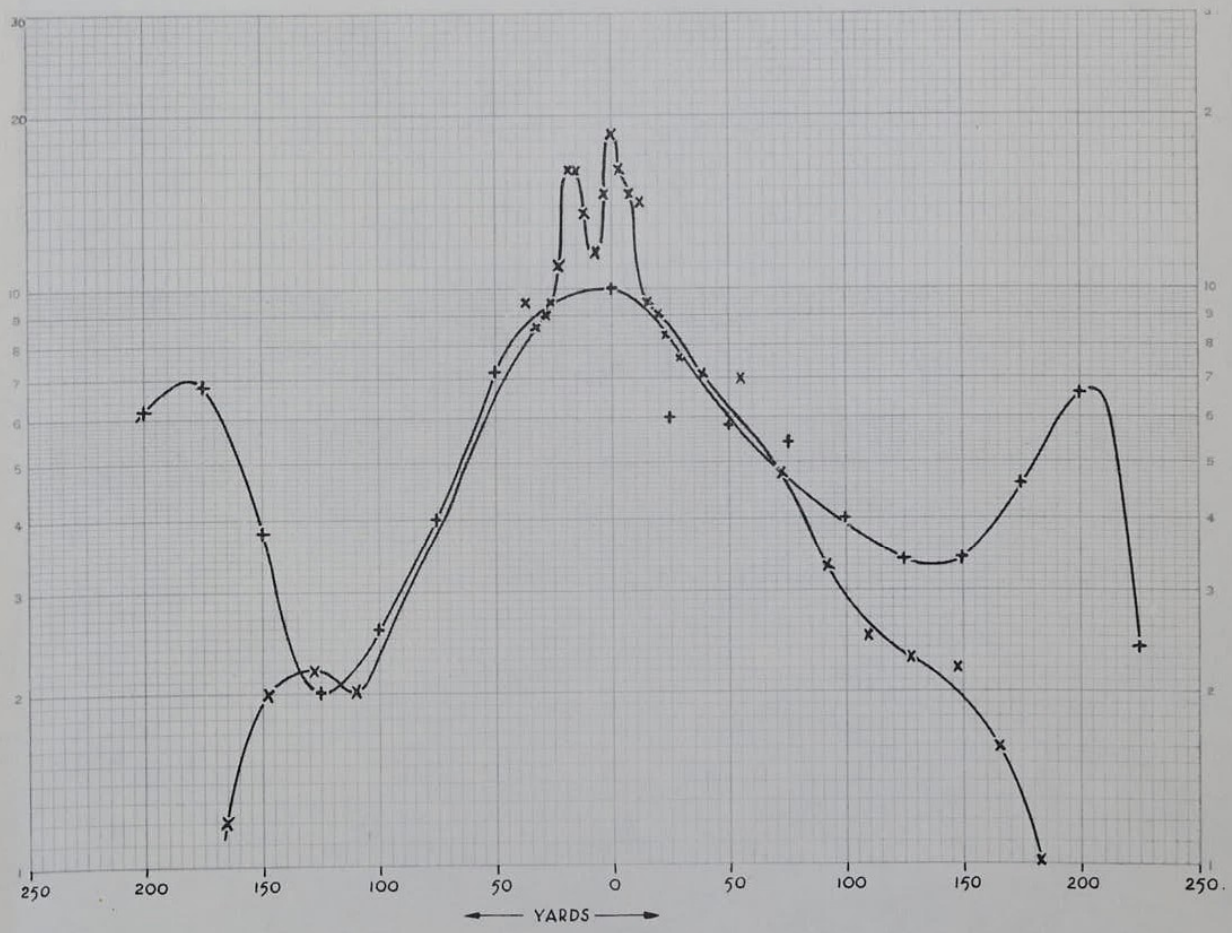

FIG. 9·1 TOTEM I CRATER SURVEY.

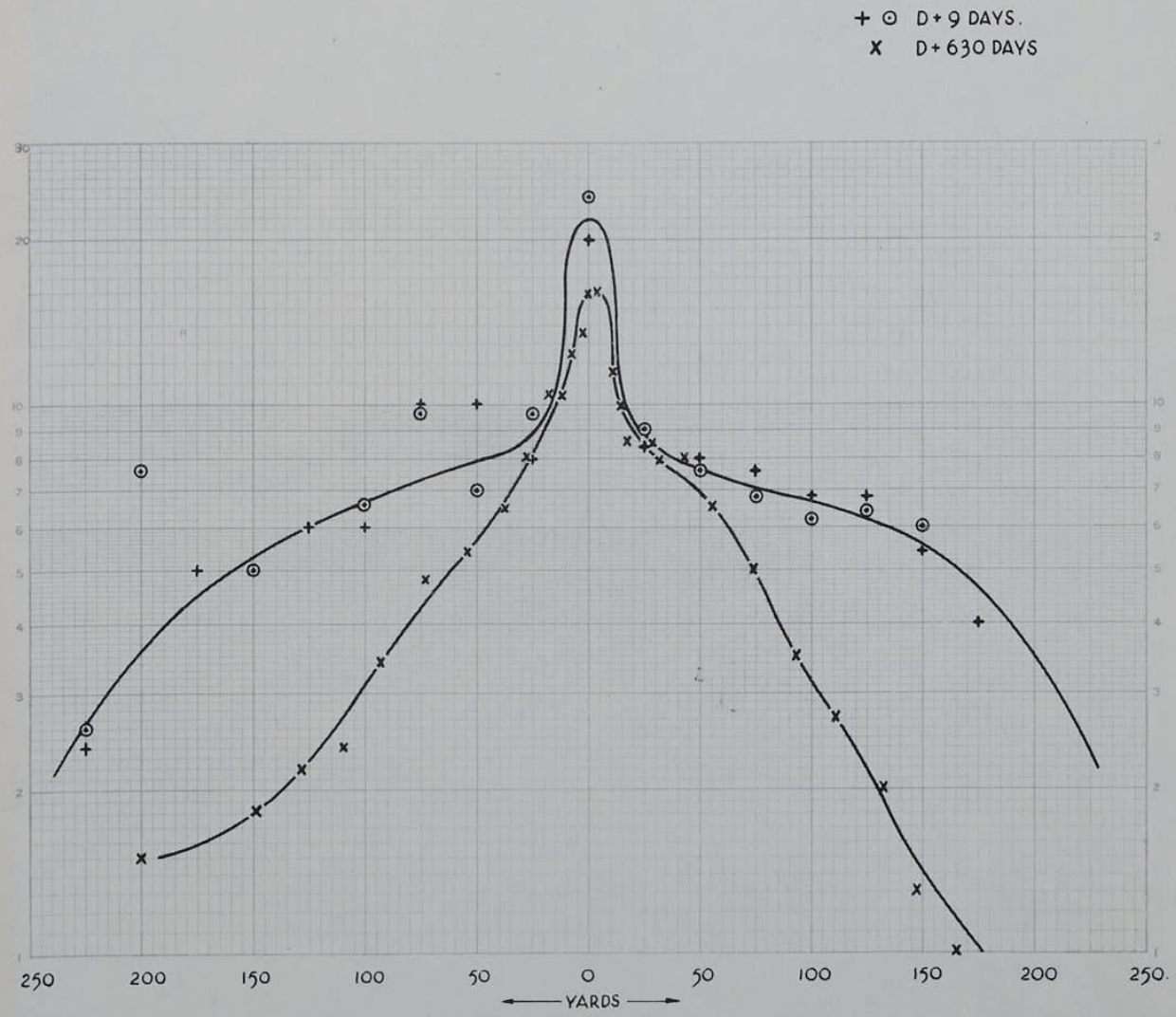

FIG. 9·2. TOTEM II CRATER SURVEY.

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ATOMIC WEAPONS RESEARCH ESTABLISHMENT

REPORT No. T 4/57

OPERATION BUFFALO

Target Response Tests

(Co-ordinator: E. R. Drake Seager)

The Decontamination of Radioactively Contaminated Drinking Water in the Field

Maj. D. B. B. Janisch, R. A.

et al.

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A.W.R.E.,
Aldermaston, Berks.

[redacted]

July, 1957

CONFIDENTIAL

United Kingdom Atomic Energy Authority

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REPORT NO. T4/57

OPERATION BUFFALO

The Decontamination of Radioactively Contaminated Drinking Water in the Field

Major D. B. B. Janisch, R.A., et al

Summary

A method of removing dissolved fission products from potential drinking water supplies in the field has been developed at the Water Pollution Research Laboratory (DSIR). This report deals with field trials of a 1/20 scale apparatus that was used at Operation Buffalo. The apparatus worked effectively with the exception of removal of radioactive iodine. Recommendations regarding future development policy are made.

Received on 13th May, 1957

Table of Contents

1. Introduction

1.1 Historical

Late in 1954 it was suggested to the War Office that, with the introduction and use of tactical nuclear weapons, it would not always be possible for a unit in the field to have available supplies of drinking water that were not radioactively contaminated.

It was accordingly decided that an investigation should be made into possible methods of decontaminating water in the field. This work was carried out by the Water Pollution Research Laboratory (DSIR) at Stevenage, Hertfordshire, working on a brief prepared by the War Office Representative, the Army Medical Liaison Officer and the RAF Medical Representative at AERE, Harwell.

In this brief, it was suggested that the initial development of equipment should be centred around the 200 gallon 'Regimental Water Truck', leaving the larger continuously working equipments (the Paterson 3000 gal/h and the airborne 1000 gal/h) as a second stage development.

At the time at which the brief was prepared, medical opinion considered that the organ-seeking elements strontium and barium (bone-seeking) and iodine (thyroid-seeking), were the major hazard to humans drinking radioactively contaminated water. Since that date, opinions have changed and it is now considered that during the first few days after the burst, the dose to the gastro-intestinal tract from all the fission products, is of equal, if not greater, importance. It will be seen in the report that follows that although the method was developed around removing strontium, barium, and iodine, it effectively removes a large proportion of the other fission products as well.

As far as the Armed Services are concerned, the trials at present reported are the first to have been carried out under United Kingdom auspices.

The problem is not easily predictable as the actual elements, as well as their proportions, will vary depending on the circumstances of

the explosion (i.e., underground, ground or air burst, terrain over which exploded etc.), and the time after burst that the water is treated. It is therefore probable that the relative proportions of fission products, and their absolute concentration would differ with fall-out from (say) an underground burst in clay from those resulting from a low air-burst in a sandy area.

The present report records the work carried out at the WPRL and at Maralinga. The more complicated parts of the report relating to the detailed chemistry have been relegated to appendices for the sake of clarity. In addition, footnotes explaining certain chemical terms have been added for any readers who may not be familiar with chemical phraseology.

1.2 Outline of Work at WPRL

The Water Pollution Research Laboratory developed in the first place a laboratory apparatus designed to remove the organ-seeking elements strontium, barium and iodine in particular. This apparatus proved successful when used with solutions of salts of these elements and therefore as a second phase, an apparatus was developed with the capacity to deal with the relatively high flow-rates met with in field water purifying equipments.

Two forms of this apparatus were designed: one a full-scale equipment using an actual Metafilter from an Army 200 gallon water truck, and the other, a portable apparatus working on 1/20 scale. The former equipment, working as a laboratory mock-up and handling 200 gallons of water in 20 minutes, the flow-rate in the 200 gallon water truck, showed that the combined treatment would remove activity caused by iodine (^{131}I) as iodide, strontium (^{89}Sr and ^{90}Sr), barium (^{140}Ba), cerium (^{144}Ce) and zirconium/niobium ($Zr/^{95}Nb$).

The second of the equipments incorporated one Metafilter candle in place of the eleven used in the Service water vehicle; this equipment was taken on Operation Buffalo and operated there by the War Office Radiac User Trials Team*.

1.3 Principles Used for Removal of RA Elements

The early trials indicated that a cation-exchange resin was adequate for removing strontium and barium (because they behave chemically in a manner similar to calcium), and that silvered kieselguhr would remove iodine when present elementally or as iodide†.

Accordingly, the full-scale and 1/20 scale 'second stage' equipments used these materials.

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* Major D. B. Janisch (War Office Representative, AERE), Major P. T. Thwaites and Captains M. H. Blakeney, T. T. Bunn, A. J. McCance and A. C. R. Makepeace.

† The element iodine may be present chemically as the element itself, or in an "acid radical" forming a salt with a metal. In these latter circumstances, the salt may be an iodide ($-I'$), an iodate ($-IO_3'$) or a periodate ($-IO_4'$). The reaction with metallic silver will take place only when the iodine is present as the element or as an iodide.

2. Task

The task was to produce an equipment that:

(1) would remove radioactive strontium, barium and iodine and as much other activity as possible,

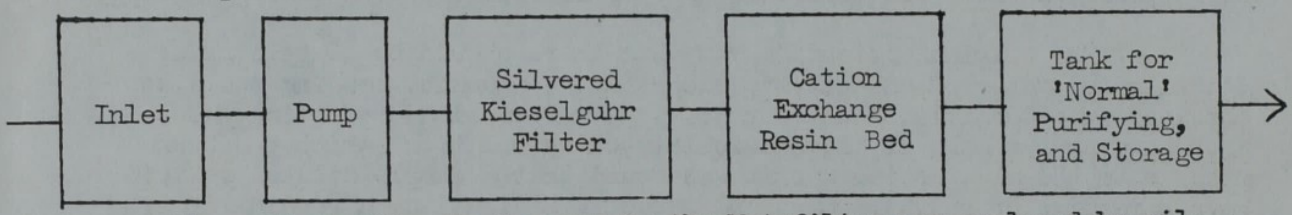
(2) would do this at the relatively high flow-rates met in Service water purifying equipment,

(3) would use relatively cheap materials, and hence, in its finished form, would not increase the cost of water purifying equipment unduly,

(4) could be incorporated in existing water equipment.

3. Method

It was found by WPRL that the process indicated in the following flow diagram was the most suitable:



The ordinary Kieselguhr used in the Metafilter was replaced by silvered kieselguhr* ; the filter bed came immediately after the pump in order to have the filtration stage as soon as possible.

Following the Metafilter, a new bed was introduced, containing a cation exchange resin† between the filter and the storage tank. Associated with this bed were the necessary by-pass and regenerating fittings.

On the 1/20 scale equipment, which is the subject of this report, the complete Metafilter which is fitted to the 200 gallon water truck and contains eleven filter candles, was replaced by one candle, so that if ten gallons were treated in 20 minutes, the flow-rate through the filter would be $\frac{1}{20} \times 11 \times 100 = 55\%$ of that on the full-scale equipment. The size of the resin bed was similarly adjusted.

An annotated photograph of the equipment is shown in Figure 1. The method of setting it up is described in Appendix A.

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* The normal variety is Metasil 'A'; the silvered variety was Metasil 'ALAG' manufactured by the Metafiltration Co. Ltd.

† ZeoKarb 225, manufactured by the Permutit Co. Ltd. This is a cation exchange resin in which ions of sodium are loosely held. Sodium ions will exchange with ions of calcium, strontium or barium when water containing the latter is passed through the bed. An ordinary domestic water softener employs an ion-exchange material.

3.1 Production of Contaminated Water

An attempt was made to collect fall-out from Round 1 (tower burst) and the top layer of a few square yards of the soil in the fall-out area was collected so that there was sufficient activity present in the sample. On sorting this soil, almost all of the activity was found to be concentrated in a small number of tiny glass-like spheres obviously consisting of fused sand. These were of course found to be almost insoluble in water; facilities were not easily available, neither was it considered expedient, to conduct the rather elaborate chemical processes necessary to bring this material into a neutral aqueous solution. Because of this relative insolubility, drinking water taken from this area would probably have been acceptable from the radioactive point of view*.

In order to obtain samples of contaminated water, the filter papers from one of the cloud-sampling aircraft in Round 3 (air burst), were used. These were macerated, and the soluble portion of the fission products leached out. The samples were collected shortly after F hour; the leaching out took place during D + 3, i.e., about 70 hours after burst, and the water was treated on D + 4, i.e., 92 to 100 hours after burst.

The original intention was that there should be 10 gallons of contaminated water of an activity such that an adequate reading would be obtained on a Contamination Meter No. 1 using the liquid counting tube. When however a sample of the original leaching solution (which had been made up to 450 ml) was tested, it was found that a sample diluted to 1:10 gave a reading of only 1.3 mr/h and one of 1:4 dilution, a reading of 4.0 mr/h. In other words, dilution of the original solution to only 1:10 would give a solution on the lower limit of contamination*. Further supplies of fall-out were not available and a decision had to be made regarding the procedure to be followed.

In view of the fact that a carrier was going to be added to the solution before treatment, it was decided that no harm would be done if the solution were diluted to the much larger volume required for the equipment, and an alternative means of measuring the activity used†.

The solution was accordingly diluted with distilled water to make up a total of 18 litres, i.e., a dilution of 1:40. All subsequent measurements of activity were made using an AERE Type 1221 Scaling Unit and a 20th Century Electronics liquid counter type M6H‡.

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* i.e., by the accepted military emergency standard, of being fit for drinking up to $2\frac{1}{2}$ litres/man/day for 10 days.

† The carrier solution consists of (non-radioactive) chemically similar substances present in much larger quantities than the fission products. Hence any chemical or physical-chemical processes will affect the radioactive substances to a proportionately small degree. The solution used here gave concentrations of about 200 p.p.m. of calcium, 0.4 p.p.m. strontium and 0.4 p.p.m. barium.

‡ The M6H counting tube is similar in basic design to the liquid counter used with the Contamination Meter No. 1, for water contamination measurements. It consists of a thin-walled (beta-sensitive) Geiger counter with a re-entrant which enables a definite amount of the liquid to be measured, to be placed around the counter itself.

3.2 Decontaminating Procedure

The diluted "fall-out solution" was divided into four portions of approximately a gallon each. Each of these portions was passed through the equipment and treated. The circumstances of treatment varied slightly from portion to portion, e.g., some portions were passed through an ordinary (unsilvered) kieselguhr filter, while for others, the ion-exchange bed had been regenerated. Full details are given in Appendix B.

4. Results

Detailed results are given in Appendix C.

From these results, it will be seen that:-

(1) Activity of untreated contaminated water fed into equipment (Portions A, B, C or D) *: 2460 counts/min.

(2) Activity of 1st. gallon after treatment (A_t): 136 counts/min.

(3) Activity of 2nd. gallon after treatment (B_t): 323 counts/min.

(4) Activity of 3rd. gallon after treatment (C_t): 382 counts/min.

This indicates that approximately 95% of the gross activity was removed from the 1st. gallon during treatment but that the efficiency dropped to 85% on the subsequent two gallons. This was using a silvered kieselguhr filter and the same ion exchange bed throughout.

Treatment of portion D with an unsilvered kieselguhr filter and with an ion exchange bed that had already treated three gallons, removed only about 60% of the gross activity. However when this portion was reprocessed (as D_t) through a new ALAG filter and a regenerated ion exchange bed, virtually no activity was detectable in the effluent D_{tt}.

The effluent from the third gallon to be processed (C_t) was reprocessed through a filter bed and ion exchange bed that had already treated one gallon, and shewed a reduction of activity from 382 counts/min to 147 counts/min, a figure in line with the activity remaining in A_t.

When the ion exchange bed was regenerated, a sample from the washings shewed an activity of 3332 counts/min. It is to be assumed that the majority of the activity removed by the ion exchange bed was washed out in regeneration. Hence the activity from 18 litres of solution (portions A, B, C and D) that had been removed by the resin, was concentrated into the 1.25 litre of regenerant washings. Presumably therefore, had these washings been diluted to the original 18 litres, the activity recorded would have been

*The four portions of solution are referred to as A, B, C and D. After one pass through the apparatus, the effluents are referred to as A_t, B_t, etc. The effluents of portions treated twice are referred to as A_{tt}, etc.

$332 \times \frac{1.25}{18}$ = 232 counts/min, as compared with 2460 counts/min recorded for the raw water, i.e., only 10% of the total activity. This however is of the same order as the proportion of strontium and barium likely to be present in the raw water.

Samples of both the raw water and of the third gallon after one and two treatments (C_t and C_{tt}) were returned by air to the WPRL who subsequently carried out radio-chemical analysis on them. Their results are given in Appendix D.

5. Conclusions and Discussion

The results in Appendix D, Table D1 show that the major active constituent in the effluent was iodine (only 31% of the total having been removed in the sample sent to the WPRL), while upwards of 91% of the strontium and barium was removed.

It should also be borne in mind that iodine occurs in fission products in a relatively high proportion.

The evidence in Appendix D, Section D2, suggests that a large proportion of the iodine activity in the air filter samples which WPRL had received, was present in a reducable anionic form such as iodate, and not, as has been suggested, as iodine or iodide.

If the proposed method of treatment is to be further developed, and if efficient removal of iodine continues to be specified, it will be necessary to find a method of treatment which will remove all the chemical forms in which radio-iodine is likely to occur in fall-out.

The equipment used at Maralinga was designed to remove strontium, barium and iodine (as elemental iodine or iodide) specifically.

Reference to Appendix D, Table D1 shows that these three elements constituted approximately 15% of the total activity in the raw sample, while in the effluents, the proportion of fission products other than iodine was fairly small. This shows that during the removal of Sr, Ba and I, the other fission products are removed to a considerable extent.

The reasons for the variations between the proportions of iodine removed after one pass (31% at Maralinga and 22% at the WPRL) and after a second pass (80% at Maralinga) are not clear. Some form of reduction of the iodine from a more highly oxidised form must presumbaly have taken place.

It will be noted that when the iodine in the solution used in the parallel series of WPRL trials was intentionally reduced chemically a similar proportion of the iodine was removed to that removed during the second pass at Maralinga.

5.1 Hazard to Operators

It must be remembered that whatever form the final equipment may take, nearly all the activity present in the raw water will be concentrated in the filter bed, ion-exchange bed and any other bed subsequently developed. When these beds are replaced or regenerated, as they will have to be after every 200 gallons on the Regimental Water Truck, or after equivalent times on other equipments, this activity is going to be washed out in a comparatively concentrated form.

If it is assumed that in its final form, the method is capable of removing 95% of the gross activity, then as a first approximation, there can be as much as 500 millicuries of active waste to dispose of after each 200 gallons (the calculation shewing this is given in Appendix E). Similarly with the Paterson 3000 gal/h equipment, over 5 curies per hour may have to be disposed of.

This is of no major consequence, but it should be borne in mind should development of this equipment for Service use proceed. For example, it will be necessary for the operator to keep at a distance from the beds except when it is actually necessary for him to approach, and for special precautions to be taken when removing the washings. As an example of the hazard, a dose-rate of the order of 1 r/h will be received at 2 ft from a point source of one curie of active material of similar energy to fission products.

The beta hazard will be of much less consequence as containers of sufficient thickness to be used on the water purifying equipment would adequately shield the operator against beta radiation. Similarly, if the washings were moved away for dumping in (say) jerricans, the material of the can plus shielding by the water of the solution, would adequately reduce the hazard to one of negligible proportions compared with the gamma hazard.

6. Recommendations

With the exception of iodine, the method developed by the WPRL shows considerable promise in removing fission products from potential drinking water supplies. A method of removing iodine in all its chemical forms still requires development: it is understood that this is feasible.

It is considered that sufficient basic research has been carried out on this method, to enable a Research and Development requirement to be laid down, should it still be considered operationally necessary to have an equipment of this nature.

In view of the fact that all the apparatus and trained personnel are at the WPRL, it is strongly recommended that any future work should be carried out there, if necessary on some form of extra-mural research contract.

7. Acknowledgment

The authors wish to express their gratitude to the Water Pollution Research Laboratory for their great assistance in this work.

APPENDIX A

Method of Setting-Up the Equipment

The ion-exchange column 'F' was charged with the resin, supplied in the fully regenerated condition, by placing it in water in the brine tank 'D' and washing it into the column through cock 'E'.

The filter bed 'B' was formed by removing the top of the filter and pouring in a slurry of the appropriate grade of kieselguhr, subsequently replacing the top and forming the filter bed on to the candle by pumping water through at a slow rate.

(The letters above refer to the annotated photograph in Figure 1.)

APPENDIX B

Decontaminating Procedure

(1) As mentioned in the main report, the 'fall-out solution' was diluted to a total volume of 18 litres, and was then divided into three volumes of approximately one gallon each and one of slightly less than one gallon. These are referred to in the remainder of the report as portions A, B, C and D. The same samples after treatment in the equipment are referred to as A_t, B_t, C_t and D_t. Any portions which were passed through the equipment twice are referred to as A_{tt}, B_{tt} etc.

(2) A background count was taken using the counting tube filled with distilled water. Following this, a count was made of a sample of the original solution diluted 1:100. An approximate cross reference between the readings obtained with the Contamination Meter No. 1, and the AERE 1221, is therefore possible.

(3) After washing out the counting tube, the background was taken again, and then a sample of the 1:40 solution was counted (i.e., a sample from A, B, C or D).

(4) Portion A was then passed through the equipment and the effluent run off into a 1 gallon glass jar (as sample A_t).

(5) Portion B was then passed through the equipment immediately after A and was run off into a separate jar as B_t.

(6) Portion C was then treated similarly.

(7) Concurrently with this, counts were made on samples from B_t, C_t and A_t (in that order).

(8) After passing portion C through the equipment, the filter bed was washed out and the Metasil ALAG (silvered kieselguhr) was replaced with Metasil A (ordinary kieselguhr). The ion exchange bed was not touched. The remaining $\frac{3}{4}$ gallon (portion D) was passed through this new filter and a sample from the effluent D_t was counted.

(9) The ion exchange bed was then regenerated with brine solution and a sample from the washings was counted. The total volume of brine + washings was 1250 ml.

(10) The Metasil A in the filter was then replaced by fresh Metasil ALAG, and B_t was again passed through the equipment which now had a new filter and a regenerated resin bed. A count was made on a sample from the effluent D_{tt}.

(11) C_t was also reprocessed and a count made on a sample from effluent C_{tt}.

APPENDIX C

	Relevant Section in Appendix B	Time of Count (from F hour)	Period of count, min	Count	Count, counts/ min	Corrected Count, counts/min	Corrected Count Less b/g	Remarks
a. Background count at start using distilled water	(2)	91 h 35 m	5	72	14	14	-	
b. Sample of original solution diluted 1:10	Report Section 3.	91 h 40 m	-	-	-	-	-	1.3 mr/h on Contamination Meter No. 1.
c. Sample of original solution diluted 1:3	Report Section 3.	91 h 45 m	-	-	-	-	-	4.0 mr/h on Contamination Meter No. 1.
d. Sample of original solution diluted 1:100	(2)	92 h 0 m	5	5135	1027	1034	1020	
e. Sample of original solution diluted 1:40 i.e., portions A to D	(3)	92 h 10 m	5	12195	2439	2479	2465	
f. Sample of original solution diluted 1:40 i.e., portions A to D	(3)	92 h 15 m	5	12129	2426	2466	2452	
g. B/g count after (f)	-	92 h 25 m	5	805	161	161	-	
h. Sample from effluent B_t	(7)	93 h 15 m to 94 h 45 m	90	43454	483	484	323	
j. B/g count after (h)	-	94 h 55 m	5	620	123	123	-	
k. Sample from effluent C_t	(7)	95 h 15 m	5	2518	504	505	382	
l. Sample from effluent A_t	(7)	95 h 20 m	5	1287	259	259	136	
m. Sample from effluent D_t	(7)	95 h 40 m	5	5379	1076	1083	960	
n. B/g count after (m)	-	95 h 45 m	5	680	135	135	-	
p. Sample of regenerant washings	(9)	96 h 25 m	5	16950	3390	3467	3332	
q. Sample from effluent D_{tt}	(10)	96 h 45 m	5	694	139	139	4	
r. Sample from effluent C_{tt}	(11)	97 h 10 m	5	1411	282	282	147	

APPENDIX D

Results of Laboratory Trials at WPRL

D.1 Examination of Samples of Water Returned from Maralinga

These were samples of untreated water (i.e., A, B, C or D), and of C_t and C_{tt}.

TABLE D1

Sample	Hardness as $CaCO_3$, p.p.m.	μc per litre at D + 13			
		Gross $\beta\gamma$	^{131}I	^{89}Sr	^{140}Ba
Untreated (Sample C)	196	0.887	0.107	0.0177	0.052
3rd. gallon after one treatment (C_t)	1.9	0.087 (90%)	0.074 (31%)	0.00025 (99%)	0.0046 (91%)
3rd. gallon after two treatments (C_{tt})	2.5	0.030 (97%)	0.0217 (80%)	<0.00001 (> 99%)	0.000113 (99.8%)

NOTE: Percentages in brackets indicate percentage removal represented by the entry immediately above.

D.2 Parallel Laboratory Trials

For a parallel but separate series of laboratory experiments, a contaminated water was made up by adding 50 ml of the extract from a sample of an air filter from Round 1 to 20 gallons of unfiltered reservoir water from the Lea Bridge Works of the Metropolitan Water Board. WPRL then used an apparatus developed by them for investigations into the removal of iodine by silvered kieselguhr.

The water was pumped through the Metafilter charged with 50 grams of Metasil ALAG at a rate of 13.8 gallons in 20 minutes. This corresponds to about 60% of the maximum rate employed in the 200-gallon unit. Part of the filtrate was passed through a small cation exchange column at a rate corresponding to the use of an 8-litre resin column at the rate of 200 gallons in 20 minutes. The regeneration level was equivalent to 20 lb per ft^3.

Analysis of representative samples of the water before and after treatment gave the results show in Table D2.

TABLE D2

Results of Laboratory-Scale Decontamination of Water

Sample	μc per litre at D + 7			
	Gross $\beta\gamma$	^{131}I	^{89}Sr	^{140}Ba
Influent	0.274	0.032	0.013	0.0249
Effluent	0.112	0.025	< 0.0012	0.00025
Percentage removal	59	22	> 91	99

In view of the low proportion of iodine activity which was removed by this treatment, an additional experiment was carried out using active material from a Round 3 air filter. A 20-gallon batch of contaminated water was prepared as in the preceding experiment and was passed at the rate of 1 gallon per minute through the Metafilter charged with Metasil ALAG. Analysis of samples of water taken before and after filtration showed no detectable change in the content of active iodine.

D.3 Notes of the Chemical Form of Iodine in Water Contaminated by Fall-Out

(1) A 10-ml aliquot of the filter extract used in the preceding experiment was treated by addition of 1 mg iodate carrier, 1 drop of 4N hydrochloric acid, and a slight excess of sulphurous acid solution. The solution was neutralised, diluted to 5 litres with unchlorinated water, and passed through a Metafilter charged with Metasil ALAG at a rate of 1 gallon per minute. The radio-iodine content was reduced by 81% on passage through the filter.

(2) When a similar volume of water containing radioactive iodide was passed through the filter the reduction in activity was approximately 98%.

(3) On passage of 100 ml of water contaminated with extract from the air filter from Round 3 through a 10 cm × 1 cm^2 column of De-acidite FF (an anion exchange resin) in the chloride form, over 98% of the iodine activity was removed.

(4) When 10 ml of the water was shaken with 1 gram of Metasil ALAG and centrifuged about 22% of the iodine activity was removed. This procedure is known to effect almost complete removal of traces of iodide from water.

APPENDIX E

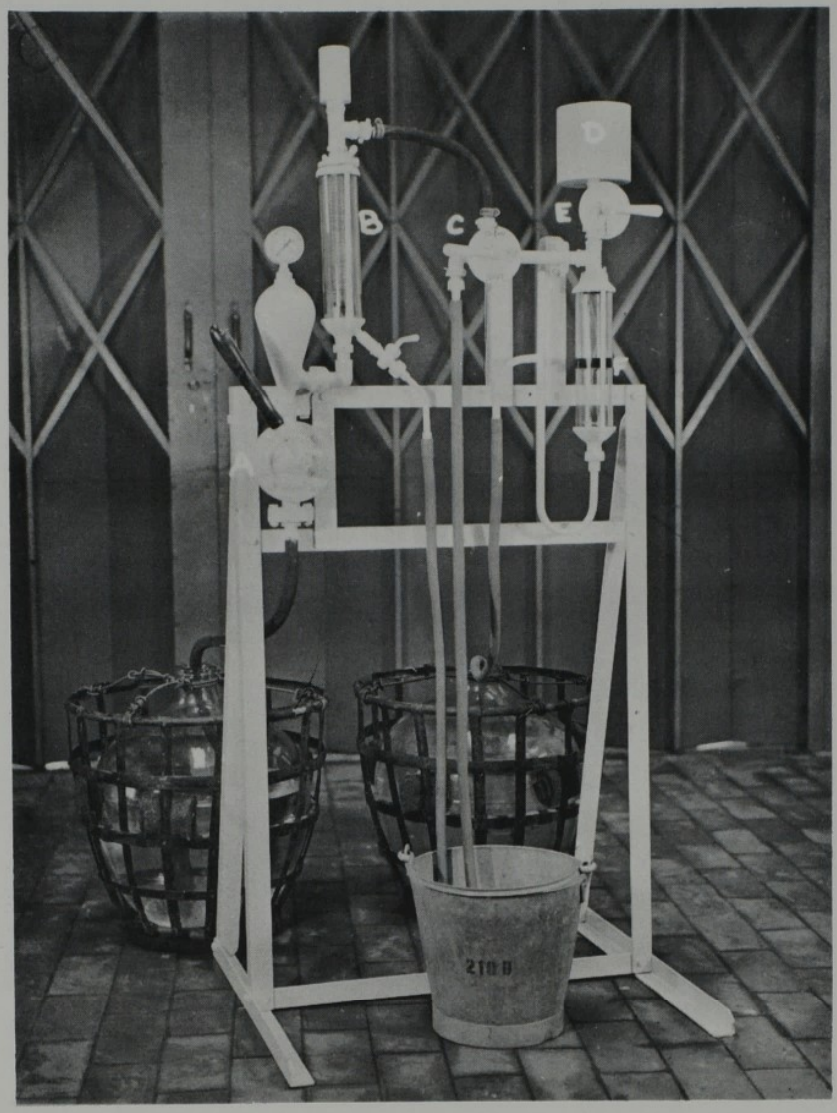
Activity to be Disposed of

Concentration of activity in final effluent aceptable for military purposes (see Section 3.1, footnote marked* on page 6) = 3×10^{-2} mc/litre.

If equipment is 95% efficient, then concentration in raw water supply can be 0.6 mc/litre.

Thus it will be possible to use water containing $0.6 \times 4.54 \times 200$ mc in 200 gallons and still produce a potable effluent. Of this, approximately 500 millicuries will be removed by the beds.

In the case of an hour's flow through a Paterson equipment, up to $0.5 \times \frac{3000}{200} =$ 7.5 curies may be removed by the beds.



Key: A Pump
B Metafilter candle and filter bed
C By-pass cock
D Brine tank
E Cock
F Ion-exchange bed

The carboy on the left of the photograph contains the raw water. That on the right receives the treated effluent. Waste, washings etc., are led into the bucket.

Figure 1.

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ATOMIC WEAPONS RESEARCH ESTABLISHMENT

REPORT No. T 37/58

OPERATION ANTLER

(32)

Target Response Group
(Group Leader Plans: E. R. Drake Seager)
(Group Leader Operations: Lt.Col. E. T. Wray, REME)

The Shielding from Initial Radiation Afforded by Soil

Maj. D. B. B. Janisch, RA

[redacted]

A.W.R.E.,
Aldermaston, Berks.

November, 1958

[redacted]

[redacted]

United Kingdom Atomic Energy Authority

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The Shielding from Initial Radiation Afforded by Soil

Maj. D. B. B. Janisch, R.A.

Summary

During both Round 2 and Round 3, measurements of γ-radiation doses and neutron fluxes were made at depths below the surface of the ground varying from 1 ft to 6 ft. Protection factors have been calculated. The experiments have shown that serious errors are likely to occur when measuring the γ-radiation dose from certain types of weapon with a quartz fibre or other ionization chamber type of dosimeter.

[redacted]

Table of Contents

Table of Contents (Cont.)

1. Introduction

On Operations Hurricane, Totem and Buffalo, trials were carried out to measure the protection from initial radiation afforded by various fieldworks and AFVs. The most recent of these trials (Operation Buffalo) is reported in Ref. [1].

After Operation Totem, Major L. Cave, RAOC, who had carried out some shielding trials, made recommendations for future trials (which are included as an Appendix to Ref. [1]). Some of the recommended trials were included in the plan for Operation Buffalo.

When analysing the results obtained at Operation Buffalo, it became clear that it was desirable to obtain more information about the shielding capabilities of earth in circumstances where confusion of the results by scattered radiation could not occur. After Operation Totem, one suggestion was to sink a small diameter pipe into the earth, and to place therein dosimeters at different depths. While making the initial preparations for the Antler trial, it was thought desirable to measure neutron fluxes as well as the γ-dose at different depths, because it had been shown in Ref. [1] that in some circumstances, the neutron hazard in a shielded position is as great as, or even greater than the γ-hazard. To accommodate neutron dosimeters, it was necessary to use a pipe of wider diameter than had originally been suggested; this necessitated a change in the method of the trial, which is described in detail in Section 3.2 below.

The protection afforded by the earth against neutrons, and against γ-radiation, has been treated separately in the remainder of the report.

As in previous reports, the Protection Factor (PF) has been defined as:-

$$PF = \frac{\text{Free air dose or flux at site}}{\text{Dose measured at particular point in shielded position}}.$$

2. Objects of the Trial

The objects of the trial were firstly to determine the protection factors afforded at various depths in soil, against γ-radiation and thermal and fast neutrons, and secondly to investigate any variation of these protection factors with distance from point of burst, weapon design or height of burst.

3. Method

3.1 Types of Dosimeter Used

3.1.1 γ-Dosimeters

It was decided to use three types of γ-dosimeter:-

(a) Service Phosphate Glass.

(b) AWRE Film/Phosphor.

(c) Service (or Service Type) Quartz-Fibre. Three varieties of these were used:-

(i) Type QF(A) The Prototype Dosimeter No. 5 used at Operation Buffalo.

(ii) Type QF(B) The Service Dosimeter No. 5.

(iii) Type QF(C) QF(B) with the ionisation chamber partially evacuated to 1/3 atmospheres and with the capacitance adjusted accordingly.

The differences between these three types of quartz-fibre dosimeter, and the reasons for their use are discussed in detail in Section 4.2 below.

3.1.2 Neutron Dosimeters

The standard AWRE method of neutron dosimetry [1] is to expose samples of pure elements in a steel tube 18 in. long, 2 in. external diameter and about $\frac{1}{4}$ in. wall thickness. The elements become radioactive on irradiation and it is possible to measure fast (greater than 3 MeV) neutrons using sulphur*, total slow neutrons using unclad gold† and epithermal neutrons using gold clad with cadmium. The thermal neutrons may then be obtained from the latter two results by subtraction.

For the present trial a modified form of the AWRE standard tube was used. This was 6 in. long, 2 in. external diameter and about $\frac{1}{4}$ in. wall thickness and contained three discs, one of gold, one of gold wrapped in cadmium and one of sulphur. A tube, with its contents, is shown in Figure 1.

3.2 Positioning of Dosimeters

The original suggestion was to sink a 2 in. diameter pipe into the ground; the angle subtended at the mouth of the pipe by any distance-piece separating dosimeters would then have been sufficiently small for its density to be unimportant. In this trial, however, it was necessary to accommodate the neutron dosimeters as well, and as it was essential that all three elements in these dosimeters should be at

---

* ^{32}S (n,p) ^{32}P . (Half-Life = 14.3 days).

† ^{197}Au (n,γ) ^{198}Au . (Half-Life = 2.69 days).

the same depth, a wider tube was necessary. Finally, it was decided to have 7 in. diameter holes made in the ground by a well-boring machine which was available. It was not desirable to employ the alternative method of blowing a crater and back-filling since this would introduce unknown variations in the density of the earth surrounding the shield.

A series of holes were bored to a depth of not less than 6 ft, at varying ranges from the Ground Zero of Rounds 2 and 3. Twin holes were dug at each site - the holes being separated by a distance of 3 ft, on a line at right angles to the radius from Ground Zero. For various administrative reasons, it was not found possible to sink twin holes for Round 2, and there were five single holes at ranges from 1350 to 2850 ft approximately from Ground Zero. For Round 3, twin holes were sunk at six sites from 1650 to 3500 ft slant range from the expected point of burst.

The holes were lined with thin steel tube to prevent caving in. To maintain the density of the shield within the tube, and at the same time facilitate the recovery of the dosimeters, the latter were placed at pre-determined positions in cylindrical cans of thin sheet steel which were subsequently filled with soil. These cans were slightly less in diameter than the bore of the holes, and had loops so that they could be lowered into the holes by a "shepherd's crook". The positions of the dosimeters were such that, when the cans were lowered into the holes, they were at the correct distances below the surface. A cross-section of a typical hole is given in Figure 2, and photographs of the cans, sunken pipes, etc. are given in Figures 3 - 6.

3.3 Distribution of γ-Dosimeters

The depths at which particular types of dosimeters were used were decided from the doses which were predicted from theoretical considerations and experience at Operation Buffalo. Thus phosphate glass and quartz-fibre dosimeters were not placed where the predicted dose was less than 10 r. The quartz-fibre dosimeters would not have been used anywhere where the dose was expected to exceed 1000 r, had

it been possible to predict the received dose accurately, but because of uncertainties regarding the yield and design of the weapons actually fired, quartz-fibre dosimeters were placed alongside the phosphate glass dosimeters throughout. There was always an overlap between the higher reading dosimeters (phosphate glass and quartz-fibre) and the film/phosphor dosimeters. Very few type QF(C) dosimeters were available, and these were placed at positions where doses of between 300 r and 500 r were expected. Unfortunately in several cases the predictions were not sufficiently accurate to ensure that the dose actually received lay within this range. A summary of the distribution of the γ-dosimeters is given in Table 1.

TABLE 1

Distribution of γ-Dosimeters

Type of Dosimeter	No. of Dosimeters at Each Depth	
	Round 2	Round 3
Phosphate glass	2	2 × 2 = 4
Film/Phosphor	1 pack	2 × 1 = 2 packs
QF(A)	2	2 × 2 = 4
QF(B)	2	2 × 2 = 4
QF(C)	1 at selected depths only	1 at selected depths only

NOTE: The numbers of dosimeters in Round 3 were doubled in most cases, a complete set being placed in both of the holes at each range.

3.4 Distribution of Neutron Dosimeters

(a) Round 2

One tube (containing one sulphur disc, one clad gold disc and one unclad gold disc) was placed at each 12 in. position down each hole, i.e., at 12 in., 24 in. .....72 in.

(b) Round 3

One tube was placed at each 12 in. position down one of the twin holes at each position.

3.5 Protection from "Loose" Contamination

To prevent contamination of the dosimeters by soil rendered radioactive by the neutron flux, all the dosimeters were wrapped in polythene bags before placing into the cans. To prevent sand from being blown down the small gap between the cans and the tube during the time between "loading" the tubes and firing, and also to prevent sand and small stones being forced into the gap by the blast, a grommet of adhesive tape was wrapped round the top of each of the uppermost cans, which were then forced into position, making a virtually dust-proof seal.

3.6 Collection of Dosimeters

Recovery of the dosimeters was made as soon as possible after burst; the average time was about two hours. The recovery parties withdrew the cans with the "crooks" and placed them, as they were, into a Landrover trailer. As soon as all the cans were recovered, the parties withdrew to an area where the dose-rate was reasonably low, and the cans were then emptied out, and the dosimeters, still in their polythene wrappings, placed in containers. The latter were then taken to an area near Health Control where the dosimeters were unwrapped. As they were uncontaminated, it was possible to take them to the Village Laboratory area where they were read or measured.

3.7 Collation of Results

(a) γ-Dosimeters

The QF dosimeters were read in the normal way, and the results recorded. Certain correction factors had to be applied; this was done after return to the U.K.

The phosphate glass dosimeters were read on a reader in the usual manner, and the results recorded for information; as however there was some doubt about the calibration of the reader, the dosimeters were brought back to the U.K. where they were read on a standard reader in the Electronics Division of AERE where the dosimeter had been developed. The film/phosphor dosimeters were handed over to the RM Group at Maralinga, who processed the films and supplied the results to the author.

(b) Neutron Dosimeters

The elements from the neutron dosimeters were, as was mentioned above, activated by the neutron flux. In order to evaluate the flux, it was necessary to measure the amount of β-activity induced in the elements concerned. Measurements of β-activity were made on a standard Geiger-Muller counter and scaling unit - a 2 in. diameter type 2B2 end-window counter was used in association with a "Scaling Unit AERE Type 1221C" and associated power supplies. Counts were made of the dosimeter samples at intervals until decay curves which were plotted showed that the half-life was correct for the isotope whose measurements were required. These counts were then normalised to a standard shelf in the lead castle and extrapolated back to the time of burst. The position of the G-M tube relative to the standard shelf in the castle was calibrated by the use of a standard thallium source lent by the RM Group. This had been employed by them for calibrating the counting equipment which they were using for a similar purpose with their neutron dosimeters, the results of which would be used for the free-air flux/distance curves.

Some of the gold samples from Round 3 were so active that it was not possible to measure them on the equipment mentioned above until several half-lives had expired. In

some cases, this would have caused an untoward delay in leaving the range, so these samples were measured approximately at Maralinga, and then returned to the U.K. by air with the minimum of delay; on arrival in the U.K., the samples were taken to the Rutherford Laboratory of the Royal Military College of Science at Shrivenham, where measurements continued until the criterion given above had been met. A standard thallium source was also returned with these samples, so that it was possible to perform an accurate cross-calibration between the two sets of equipment, and to normalise the Shrivenham results to the same norm as was used for the Maralinga results.

The half-life of the phosphorus (^{32}P), measured in the sulphur samples from Round 3, is so long that measurement at Maralinga would have caused unnecessary delay. These samples were treated in the same manner as the gold ones mentioned above.

The normalised counts per unit time obtained were converted to neutron fluxes by using conversion factors which had been evaluated by the RM Group for converting their own results. The same factors were therefore used throughout by the RM Group and the author, thus preventing any errors in the protection factors which were calculated therefrom.

4. Results

4.1 γ-Dosimetry Results

Details of the γ-doses which were measured, and of the protection factors, are given in Appendix A. The Protection Factors are also shown graphically in Figures 7(a), 7(b), 10(a) and 10(b).

4.2 Reliability of Results

4.2.1 Quartz-Fibre Dosimeter

Certain types of quartz-fibre dosimeter are liable to read low when measuring large doses of γ-radiation delivered over a very short period of time [1], [2], [3]. To give the reasons for the decisions which are made below, it is necessary to give a brief resume of the situation regarding Service QF dosimeters over the period covering Operations Buffalo and Antler.

Originally, quartz-fibre dosimeters intended for measuring initial radiation (as opposed to residual radiation), were designed on the assumption that the substantial portion of the dose would be delivered at a dose-rate not exceeding 100 r/sec. As a result of experience on Operation Buffalo, it was decided that the Service dosimeter QF No. 5 should be calibrated so as to read full-scale doses accurately when delivered at dose-rates up to 600 r/sec [4]. This was possible for two reasons, firstly that the Service design (type QF(B) in this report) had improved geometry compared with the prototype (QF(A)), and secondly, that the scale had been adjusted so that at dose-rates not exceeding 600 r/sec, the dosimeter would read within ± 20% as opposed to + 0% − 40% as with the type QF(A).

On examination of the present results, it was found that discrepancies of up to a factor of more than 2 existed between the phosphate glass dosimeter results and those of the quartz-fibre (QF(B)) dosimeters. Even greater discrepancies were found in the case of the QF(A) dosimeters. These variations were discussed with members of the RM Group, and with the members of the Electronics Division of AERE who are concerned with the development of these dosimeters (Messrs. W. Abson, D. Peirson and F. B. Whiting). As a result of these discussions, three solutions seemed possible:-

(a) A greater sensitivity to neutrons in the case of the phosphate glass dosimeters.

(b) An inferior response by the quartz-fibre dosimeters due to the γ-radiation of energies greater than 2 MeV received from the radiative capture of neutrons in the atmosphere, **together with** the fact that any γ-radiation stemming from the neutron flux will be delivered at a high dose-rate.

(c) Increased errors in the quartz-fibre dosimeters because a substantial portion of the total dose may be delivered at a dose-rate considerably in excess of 600 r/sec.

These different possibilities of errors arising are discussed below:-

(a) Neutron Sensitivity

Phosphate glass and quartz-fibre dosimeters have been irradiated under similar conditions in a thermal reactor, and it was found that, for thermal neutrons, the sensitivity of the two types was similar and that a neutron flux of 10^{10} thermal neutrons/cm^2 enhanced the reading of either type of dosimeter by about 1 r. At the time of writing this report (February, 1958), little information was available on the relative sensitivity to neutrons with energies greater than thermal, but there is an indication that the response of both types of dosimeter to these energy neutrons is similar [6].

(b) **Variations in Energy of Incident γ-Radiation**

Differences in the surface densities of the two types of dosimeter will tend to make the quartz-fibre dosimeters read slightly low when measuring radiation with energies greater than the 2 MeV associated with the initial radiation from the cloud itself. In Ref. [7] it is shown that for the radiative capture of neutrons in the atmosphere (of which the reaction $^{14}N\ (n,\gamma)\ ^{15}N$ is one of the more important), a large proportion of the γ-photons have energies of greater than 5 MeV and some are of energies exceeding 10 MeV. In the same reference, it is suggested that, for low neutron-escape weapons, the contribution to the total γ-dose from the neutron capture reaction does not exceed 20%. It is reasonable therefore to assume that for Antler Rounds 2 and 3, where the neutron-escape was larger, the contribution of the higher energy (radiative capture) γ-rays to the total γ-dose was probably more than 50%.

Three individual errors can therefore be introduced by this:-

(i) The direct error due to the varying response of the instrument to γ-photons of different energies.

(ii) The fact that there will be greater attenuation of the lower energy (cloud) γ-radiation by the earth, so that in the deeper positions in the holes, the high energy (radiative capture) γ-rays will constitute a greater proportion of the total dose.

(iii) The time over which the two components of the γ-dose is delivered. This is discussed in more general terms below.

(c) **Errors from High Dose-Rate**

This seems to be the most probable source of error. The RM Group records show that in Antler Rounds 2 and 3, at 6000 ft from Ground Zero, approximately 35% of the total dose was delivered in 0.01 sec, and 76% in 0.3 sec* [5]. Application of these figures to a total dose of the order of 500 r. (the full-scale deflection on the dosimeter QF No. 5), shows that a large proportion of the dose must have been delivered at dose-rates considerably in excess of 600 r/sec. There is little practical confirmation that this will explain the very low relative readings of the quartz-fibre dosimeters compared with the phosphate glass, as it is not possible to simulate such high dose-rates in the laboratory with any degree of accuracy. However, it is reasonable to assume that the phosphate glass dosimeter should show less errors from high dose-rates (as it is the collection of dislodged **electrons** which is concerned in the measurement), than would the quartz-fibre dosimeter where comparatively heavy **ions** have to be collected. There is some additional confirmation from the partially evacuated quartz-fibre dosimeters (type QF(C)), which show smaller errors than the others.

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* The data given here of the proportion of the dose delivered over different periods of time include the increased dose-rate due to the γ-rays from the radiative capture of neutrons in the atmosphere.

4.2.2 Other Dosimeters

It will be noted that, in some cases, there are discrepancies between the phosphate glass and the film/phosphor dosimeter readings. There is insufficient evidence to show which is correct, and for this reason, protection factors calculated for these results have been shown as a range.

It has been decided to use the phosphate glass dosimeter results in preference to any others when calculating protection factors, for the reasons given above, and also from information from Operation Buffalo. In Ref. [3], it is shown that in general, the phosphate glass dosimeter readings show better agreement with other methods of dosimetry than do the quartz-fibre.

The phosphate glass dosimeter readings which have been used have been adjusted to allow for the contribution to the recorded dose made by the neutron sensitivity of the dosimeter.

4.3 Neutron Dosimetry Results

Details of the neutron fluxes which were measured, and of the protection factors, are given in Appendix B and the protection factors are illustrated in Figures 8(a), to 9(b) and 11(a) to 12(b).

As was mentioned in Section 3.1.2, the thermal neutron flux is calculated by subtracting from the total slow neutron flux (measured by the unclad gold) the flux of epithermal neutrons (measured by the gold wrapped in cadmium). The results given in the Appendix have been treated in this manner, and fluxes of thermal neutrons and of fast (greater than 3 MeV) neutrons only have been given. It must be remembered that there will be in the neutron spectrum at any range from the point of burst, neutrons of energies above the thermal region and less than 3 MeV which have not been

detected and measured in this trial. The necessity of measuring these intermediate neutrons was discussed in Ref. [1], but at the time of preparing for Operation Antler, there was no really reliable method of measuring them readily available.

5. Discussion

5.1 γ-Dosimetry

(a) Round 2

From the results of the γ-radiation measurements made on Round 2 (an approximately 5 kiloton weapon burst on a 100 ft tower), it will be seen that the protection factors which were obtained in hole BI2 (1800 ft) are exceptionally high and are generally quite different from those obtained at similar depths at other positions. There is also a probably spurious low factor at 60 in. at position BI3 (2100 ft), and as this factor is determined by only one set of dosimeter results, too much reliance should not be placed on it.

In Appendix A to Ref. [1], it was suggested that for planning purposes, the following protection factors (Table 2) should be used for a ground (or low tower) burst. Mean factors obtained at Antler Round 2 are given for comparison.

TABLE 2

Predicted and Measured Protection Factors: Round 2

Depth, in.	6	12	24	36	48	60
Predicted P.F.	5	30	250	2000	2×10^4	2×10^5
Mean P.F. Obtained	2	5	30	300	2000	5000

Individual factors will of course vary appreciably from the "mean P.F. obtained" quoted above, but these latter figures are considered to be reasonably representative.

(b) Round 3

In the case of Round 3, (a balloon-burst at about 1000 ft of a 25 kiloton weapon) there were, unfortunately, some serious discrepancies between readings obtained by phosphate glass and film/phosphor dosimeters at 48 in. depth at positions TA4, TA5 and TA6. The results which are available are compared with those predicted in Ref. [1] in Table 3 below.

TABLE 3

Predicted and Measured Protection Factors: Round 3

Depth, in.	6	12	24	36	48	60
Predicted P.F.	1.7	10	80	400	4000	4×10^4
Mean P.F. Obtained	1.3	3	15	85	1000	$3\frac{1}{2} \times 10^3$ to $2\frac{1}{2} \times 10^4$

It will be seen that in the case of both rounds, the protection factors obtained were appreciably lower than those which were suggested. (It must be emphasised that the author of those suggestions said at the time that accurate prediction was very difficult.)

The manner in which the well-boring machine deposited the spoil on the surface made it impossible to analyse the material being bored out; Figure 4 shows typical spoil. One possible explanation of the higher protection factors measured at position BI2 would be that the hole was bored into sand instead of limestone; there was however no sign of this in the spoil. It would of course be possible for the area of the hole to be surrounded by a pocket of higher density sand although the hole itself was bored in limestone - this is considered unlikely.

5.2 Neutron Dosimetry

In Round 3 the exceptionally low protection factors afforded against thermal neutrons by 12 in. of soil are noteworthy. This is presumably due to the fact that the top foot of soil in situations like Maralinga contains few of the elements which are good absorbers of thermal neutrons.

There are variations in the factors for thermal neutrons at greater depths, but generally speaking, the variations are not excessive.

The protection factors for fast neutrons are more consistent.

6. Conclusions

This series of experiments has produced some more data on the shielding properties of the soil and subsoil from γ and neutron radiation, but the results obtained are still too variable from position to position to be of much value when designing field-works and other shelters. The uncertainty is accentuated when the varying designs of weapon are taken into account, as variations in the relative neutron escape will (a) change the γ-spectrum, and hence the γ-radiation protection factor, and (b) alter the relative hazard of the γ-rays and the neutron flux to persons within the shelter*.

These results confirm the conclusions arrived at in Ref. [1], namely that the protection factors predicted from data relating to low neutron-escape weapons are not valid for weapons of other design.

---

* The question of the relative neutron hazard was discussed in Ref. [1] and will not be repeated in this report, except to summarize the suggestions given therein on the relative biological hazards from acute doses of γ and neutron radiation. These suggestions were:

  3×10^9 thermal neutrons cm^{-2} or 3×10^7 fast neutrons cm^{-2} are equivalent biologically to 1 r of external whole body γ-radiation for short periods of irradiation, i.e., acute doses.

With high neutron-escape weapons, the rate of delivery of the γ-dose would appear to be so fast that instruments which are based on ionisation chambers, such as quartz-fibre dosimeters, are unable to collect all the ions produced in the chamber, and hence are liable to read low to an extent which makes it doubtful whether the reading has any real meaning.

The conclusion reached in Ref. [1] on group dosimetry again appears to hold. In that reference, it was suggested that the determination of the dose received by an individual from that measured by a "group dosimeter" was likely to be very misleading unless the exact position of the individual in the shelter was known.

A method of measuring neutrons of intermediate energies in experiments such as these is still required. There is no information at present of the hazard which would have resulted, in the circumstances of this trial, from the neutrons with energies of more than thermal but less than 3 MeV.

7. Recommendations

Further information is still required on the shielding from nuclear radiations afforded by the various forms of materials which could be used in the field. This applies particularly to shielding from neutrons, which is much more difficult to predict than that from γ-radiation.

A possible method of determining the shielding properties would be to use containers holding a known volume of the potential shielding material, of which the analysis, water content and density should be accurately known. Thin metal containers similar to an ordinary domestic dustbin should be suitable, with the dosimeters inserted into the centre of the mass of material. In this way, it would be possible to import samples of other soils and subsoils. This is considered particularly important from the point of view of neutron shielding, where small changes in analysis or water content can have appreciable effects. Although not strictly relevant to this report, it should be

noted that if this proposal was adopted, it would be possible to carry out a parallel series of experiments on the degree of neutron-induced activity produced in samples of soil from different parts of the world. This information is not readily available at present, and there is a tendency to regard all neutron induced activity in soils as being almost entirely from sodium.*

Consideration should be given to the suitability of quartz-fibre dosimeters for measuring initial γ-radiation under operational conditions, in view of the poor response to radiation received at a high dose-rate. For trials purposes, it is recommended that the use of these dosimeters, in their present form, should cease.

A method of measuring neutrons of intermediate energies, suitable for use in shielding experiments, should be developed, so that the hazard from these neutrons can be investigated.

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* It would be possible to predict this activity, using the methods reported in Ref. [8] provided that the chemical analysis of the soil was very accurately known.

References

1. Maj. D. B. B. Janisch, et al.: "Operation Buffalo - The Shielding from Initial Radiation Afforded by Fieldworks and AFV's". AWRE Report No. T3/57.

2. Maj. D. B. B. Janisch et al.: "Operation Buffalo - Field Trials of Radiac Instruments in a Radioactively Contaminated Area" AWRE Report No. T2/57.

3. D. H. Peirson: "Operation Buffalo - Measurements with Phosphate Glass and Quartz-Fibre Dosimeters in the Field". AWRE Report No. T26/57.

4. G. C. Dale: Private communication on Operation Buffalo - January, 1957.

5. G. C. Dale: Private communication on Operation Antler - February, 1958.

6. D. H. Peirson and F. B. Whiting: Private communication - February, 1958.

7. R. A. Siddons: "Gamma Emission Resulting from the Radiative Capture of Neutrons by Nitrogen During an Atomic Explosion". AWRE Report No. E5/54.

8. Maj. D. B. B. Janisch: "Operation Antler - Neutron Induced Activity. AWRE Report No. T35/58.

APPENDIX A

γ-Radiation Measurements and Protection Factors: Round 2

Position and Ground Range, ft	Depth, in.	Phosphate Glass Dosimeters			Quartz-Fibre Dosimeters			Film-Phosphor Dosimeters	Accepted γ-Dose	External γ-Dose	Protection Factor
		Reading	Correction	Corrected Reading	(A)	(B)	(C)				
BI1	6	> 9000	N. A.	> 9000	O. S.	O. S.	-	-	> 9000	25610	< 2.8
(1348)	12	5025	336	4690	O. S.	O. S.	O. S.	-	4690		5.7
	24	600	34	565	200	340	O. S.	-	565		45
	36	55	0	55	35	35	-	-	55		470
	48	-	-	-	-	-	-	> 10	> 10		< 2500
	60	-	-	-	-	-	-	5	5		5100
	72	-	-	-	-	-	-	N. R.	-		-
BI2	6	1800	120*	1680	370	500+	-	-	1680	9940	5.9
(1800)	12	600	37	565	210	300	510	-	565		17
	24	55	2	55	40	60	60	-	60		170
	36	18	0	20	12	15	-	5.4	-		> 500 >1800
	48	-	-	-	-	-	-	2.0	2		5000
	60	-	-	-	-	-	-	2.5	2		5000
	72	-	-	-	-	-	-	N. R.	-		-
BI3	6	1900	100*	1800	475	O. S.	-	-	1800	4000	2.2
(2100)	12	925	67	860	225	395	O. S.	-	860		4.6
	24	220	9	210	85	120	-	> 10	210		19
	36	20	0	20	25	25	-	0.75	20		200
	48	-	-	-	-	-	-	N. R.	-		-
	60	-	-	-	-	-	-	3.3	3		1300
	72	-	-	-	-	-	-	N. R.	-		-
BI4	6	950	40*	910	400	O. S.	-	-	910	2000	2.2
(2400)	12	375	15	360	150	250	-	-	360		5.5
	24	50	1	50	30	45	-	> 8	50		40
	36	10	0	10	10	15	-	5	10		200
	48	-	-	-	-	-	-	1.2	1		2000
	60	-	-	-	-	-	-	N. R.	-		-
	72	-	-	-	-	-	-	0.34	0.3		6600
BI5	6	360	30	330	190	275	300	> 10	330	800	2.4
(2850)	18	55	2	55	35	65	-	> 10	60		13.3
	30	10	0	10	10	20	-	4.5	-		> 80 < 180
	42	-	-	-	-	-	-	1.3	1.3		600
	54	-	-	-	-	-	-	0.23	0.25		3200
	66	-	-	-	-	-	-	0.08	0.08		10^4

NOTES: O. S. = Off Scale. N. A. = Not applicable.

N. R. = Not recovered or No record.

* = Phosphate glass dosimeter correction from interpolated neutron data.

500+ = Fibre on QF dosimeter still visible.

All readings are in roentgen - final readings are rounded off.

The figures given are the mean of all the dosimeters of a particular type at that position. Any results which differ from the apparent mean by more than the specification limits (± 20%) have been rejected.

APPENDIX A (Cont.)

Round 3

Position and Slant Range, ft	Depth, in.	Phosphate Glass Dosimeters			Quartz-Fibre Dosimeters			Film-Phosphor Dosimeters	Accepted γ-Dose	External γ-Dose	Protection Factor
		Reading	Correction	Corrected Reading	(A)	(B)	(C)				
TA1	6	> 9000	N. A.	> 9000	O. S.	O. S.	-	-	> 9000	1. 7	< 20
(1410)	12	> 9000	N. A.	> 9000	O. S.	O. S.	-	-	> 9000	$\times 10^5$	< 20
	24	> 9000	N. A.	> 9000	O. S.	O. S.	O. S.	-	> 9000		< 20
	36	1650	40	1610	O. S.	O. S.	O. S.	-	1610		105
	48	115	2	115	80	115	-	> 10	115		1500
	60	-	-	-	-	-	-	7. 2	7		2.5×10^4
	72	-	-	-	-	-	-	4. 5	5		3.5×10^4
TA2	6	> 9000	N. A.	> 9000	O. S.	O. S.	-	-	> 9000	4. 5	< 5
(1750)	12	> 9000	N. A.	> 9000	O. S.	O. S.	-	-	> 9000	$\times 10^4$	< 5
	24	5500	630	4870	O. S.	O. S.	O. S.	-	4870		9. 3
	36	700	40	660	190	275	300	N. R.	660		69
	48	60	1	60	50	-	-	9. 5	-		> 760 < 4800
	60	-	-	-	-	-	-	4. 7	5		9100
	72	-	-	-	-	-	-	3. 3	3		15000
TA3	6	> 9000	N. A.	> 9000	O. S.	O. S.	-	-	> 9000	2. 3	< 2. 5
(2000)	12	> 9000	N. A.	> 9000	O. S.	O. S.	-	-	> 9000	$\times 10^4$	< 2. 5
	24	2680	219	2460	O. S.	O. S.	O. S.	-	2460		9. 3
	36	220	11	210	105	160	-	N. R.	210		110
	48	-	-	-	-	-	-	7. 5	8		2900
	60	-	-	-	-	-	-	3. 9	4		5800
	72	-	-	-	-	-	-	2. 0	2		12000
TA4	6	> 9000	N. A.	> 9000	O. S.	O. S.	-	-	> 9000	1. 2	< 1. 3
(2370)	12	7400	559	6840	O. S.	O. S.	O. S.	-	6840	$\times 10^4$	1. 8
	24	1150	92	1060	365	485	-	-	1060		11. 0
	36	170	6	165	70	120	-	> 10	165		73
	48	60	1	60	-	-	-	8. 4	-		> 200 < 1400
	60	-	-	-	-	-	-	5. 0	5		2400
	72	-	-	-	-	-	-	3. 0	3		4000
TA5	6	6300	300*	6000	O. S.	O. S.	-	-	6000	6400	1. 1
(2695)	12	2450	280	2170	O. S.	O. S.	O. S.	-	2170		2. 9
	24	410	51	360	150	245	-	-	360		18
	36	65	2	65	35	60	-	> 10	65		98
	48	20	0	20	-	-	-	3. 6	-		> 320 < 1800
	60	-	-	-	-	-	-	1. 2	1. 5		4300
	72	-	-	-	-	-	-	1. 5	1. 5		4300
TA6	6	2320	100*	2220	O. S.	O. S.	-	-	2220	3600	1. 6
(3160)	12	910	98	810	360	500+	O. S.	-	810		4. 4
	24	150	15	135	65	120	-	> 10	135		26. 0
	36	30	0	30	20	-	-	5. 9	-		> 120 < 600
	48	10	0	10	-	-	-	2. 3	-		> 360 < 1500
	60	-	-	-	-	-	-	1. 1	1		3600
	72	-	-	-	-	-	-	0. 5	0. 5		7200

For Notes, see Appendix A, page 23.

APPENDIX B

Neutron Measurements and Protection Factors: Round 2

Position	Range for Ground Zero, ft	Depth, in.	Thermal Neutron Dose, n/cm^2		Fast Neutron Dose, n/cm^2		Protection Factors	
			Measured	External	Measured	External	Thermal Neutrons	Fast Neutrons
BI1	1348	12	3.36×10^{12}	1.5×10^{13}	1.24×10^{10}	8×10^{11}	4.5	6.5
		24	3.37×10^{11}		1.72×10^{9}		4.5	470
		36	4.39×10^{9}		$< 5 \times 10^{8}$		8.4×10^{3}	1.6×10^{3}
		48	3.19×10^{8}		$< 5 \times 10^{8}$		4.7×10^{4}	1.6×10^{3}
		60	N. R.		N. R.		-	-
		72	N. R.		N. R.		-	-
BI2	1800	12	3.72×10^{11}	4.3×10^{12}	2.23×10^{9}	2.3×10^{11}	12.1	100
		24	2.05×10^{10}		$< 5 \times 10^{8}$		210	
		36	1.02×10^{9}		$< 5 \times 10^{8}$		4200	> 460
		48	2.14×10^{8}		$< 5 \times 10^{8}$		2.0×10^{4}	
		60	$< 10^{7}$		$< 5 \times 10^{8}$		$> 4 \times 10^{5}$	
		72	-		-			
BI3	2100	12	6.74×10^{11}	1.9×10^{12}	4.54×10^{9}	9.5×10^{10}	2.8	21
		24	9.04×10^{10}		1.14×10^{9}		21	84
		36	4.35×10^{9}		$< 5 \times 10^{8}$		440	> 190
		48	1.03×10^{8}		$< 5 \times 10^{8}$		1.8×10^{4}	> 190
		60	N. R.		N. R.		-	-
		72	N. R.		N. R.		-	-
BI4	2400	12	1.55×10^{11}	9.0×10^{11}	1.57×10^{9}	4.4×10^{10}	5.8	28
		24	1.48×10^{10}		$< 5 \times 10^{8}$		61	
		36	7.11×10^{8}		$< 5 \times 10^{8}$		1300	> 88
		48	4.76×10^{7}		$< 5 \times 10^{8}$		1.9×10^{4}	
		60	$< 10^{7}$		$< 5 \times 10^{8}$		$> 9 \times 10^{4}$	
		72	$< 10^{7}$		$< 5 \times 10^{8}$		$> 9 \times 10^{4}$	
BI5	2850	6	3.33×10^{11}	3.0×10^{11}	2.16×10^{9}	1.5×10^{10}	1.0	6.9
		18	1.67×10^{10}		$< 5 \times 10^{8}$		18	
		30	2.40×10^{9}		$< 5 \times 10^{8}$		130	> 30
		42	3.12×10^{7}		$< 5 \times 10^{8}$		9600	
		54	$< 10^{7}$		$< 5 \times 10^{8}$		$> 3 \times 10^{4}$	
		66	$< 10^{7}$		$< 5 \times 10^{8}$		$> 3 \times 10^{4}$	

APPENDIX B (Cont.)

Round 3 (Neutrons)

Position	Slant Range for Burst, ft	Depth, in.	Thermal Neutron Flux, n/cm^2		Fast Neutron Flux, n/cm^2		Protection Factors	
			Measured	External	Measured	External	Thermal Neutrons	Fast Neutrons
TA1	1410	12	4.44×10^{13}	8.2×10^{13}	3.53×10^{11}	2.2×10^{12}	1.8	6.2
		24	5.21×10^{12}		4.03×10^{10}		16	55
		36	4.11×10^{11}		4.76×10^{9}		200	460
		48	1.77×10^{10}		$< 5 \times 10^{8}$		4600	> 4400
		72	4.35×10^{8}		$< 5 \times 10^{8}$		1.9×10^{5}	-
TA2	1750	12	3.03×10^{13}	3.0×10^{13}	1.74×10^{11}	1.1×10^{12}	1.0	6.3
		24	6.32×10^{12}		2.10×10^{10}		4.7	52
		36	4.04×10^{11}		2.23×10^{9}		74	490
		48	1.14×10^{10}		$< 5 \times 10^{8}$		2600	> 2200
		72	1.57×10^{8}		$< 5 \times 10^{8}$		1.9×10^{5}	-
TA3	2000	12	1.36×10^{13}	1.6×10^{13}	7.32×10^{10}	6.0×10^{11}	1.2	8.2
		24	2.19×10^{12}		6.96×10^{9}		7.3	86
		36	1.08×10^{11}		$< 5 \times 10^{8}$		150	> 1200
		48	6.53×10^{9}		$< 5 \times 10^{8}$		2500	-
		72	2.71×10^{7}		$< 5 \times 10^{8}$		5.9×10^{5}	-
TA4	2370	12	5.59×10^{12}	6.0×10^{12}	3.37×10^{10}	2.7×10^{11}	1.1	8.0
		24	9.20×10^{11}		3.66×10^{9}		6.5	74
		36	6.23×10^{10}		$< 5 \times 10^{8}$		96	> 540
		48	1.12×10^{10}		$< 5 \times 10^{8}$		540	-
		72	1.63×10^{8}		$< 5 \times 10^{8}$		3.7×10^{4}	-
TA5	2695	12	2.82×10^{12}	2.9×10^{12}	1.16×10^{10}	1.4×10^{11}	1.0	12.0
		24	5.13×10^{11}		1.39×10^{9}		5.6	100
		36	1.54×10^{10}		$< 5 \times 10^{8}$		190	> 280
		48	7.89×10^{8}		$< 5 \times 10^{8}$		3700	-
		72	$< 10^{7}$		$< 5 \times 10^{8}$		$> 2.9 \times 10^{5}$	-
TA6	3160	12	9.77×10^{11}	1.0×10^{12}	4.79×10^{9}	5.1×10^{10}	1.0	11
		24	1.49×10^{11}		$< 5 \times 10^{8}$		6.7	> 100
		36	4.35×10^{9}		$< 5 \times 10^{8}$		230	-
		48	1.15×10^{8}		$< 5 \times 10^{8}$		8700	-
		72	1.56×10^{7}		$< 5 \times 10^{8}$		6.4×10^{4}	-

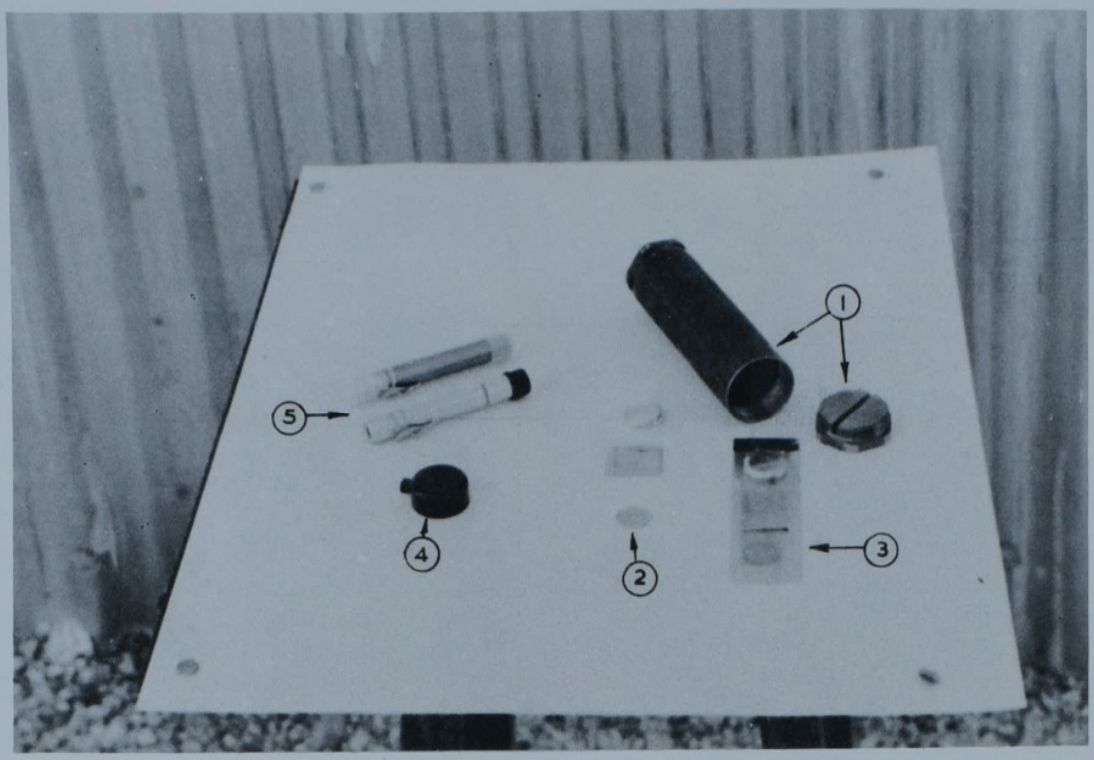

FIGURE 1. THE DOSIMETERS WHICH WERE PLACED AT EACH DEPTH.

KEY

1. THE NEUTRON DOSIMETER TUBE AND CAP.
2. THE THREE ELEMENTS (FROM TOP TO BOTTOM)
   SULPHUR, PROTECTED BY TWO ALUMINIUM PLANCHETTES.
   GOLD, CLAD IN CADMIUM.
   GOLD.
3. THE THREE ELEMENTS, MOUNTED ON THE ALUMINIUM SLIDE PRIOR TO INSERTION INTO THE STEEL TUBE.
4. A SERVICE ~~PHOSP~~HATE-GLASS DOSIMETER.
5. TWO TYPICAL QF DOSIMETERS.

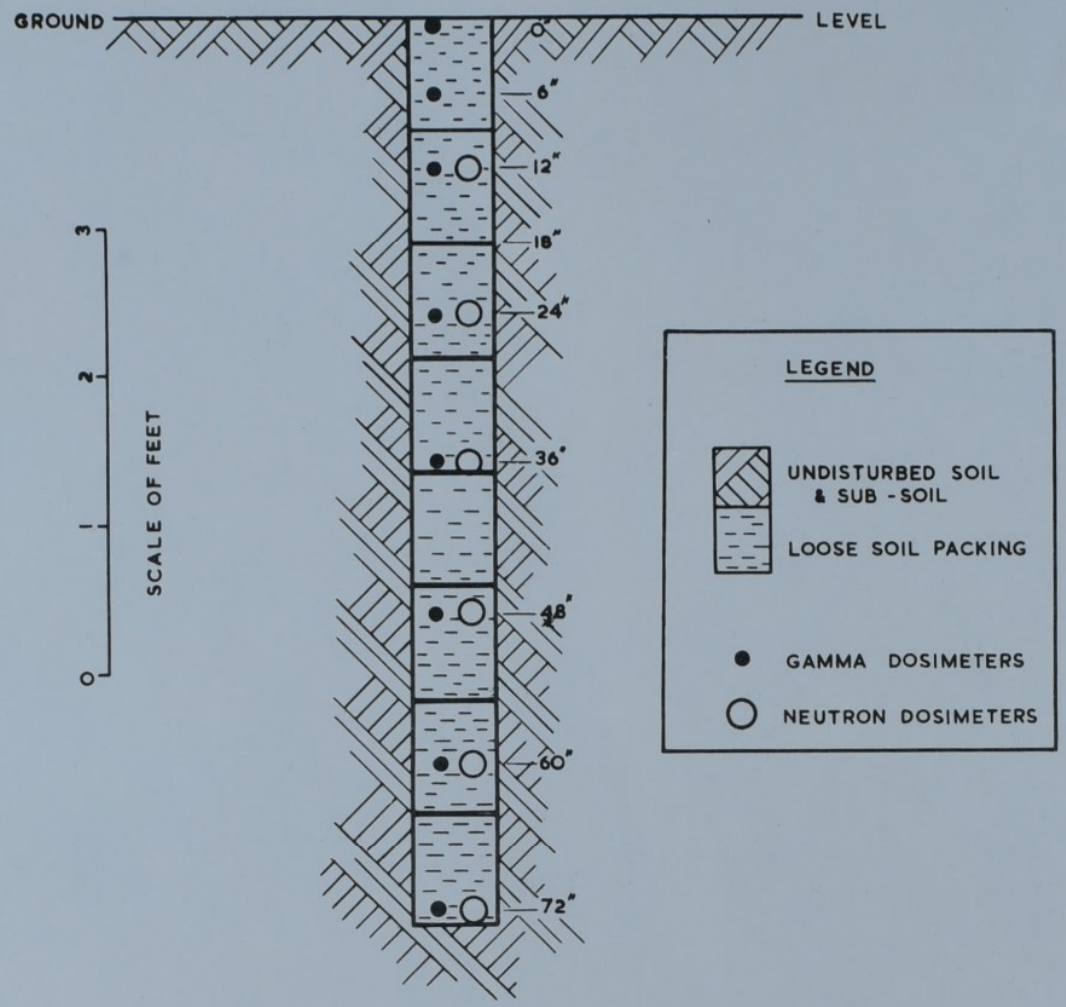

FIGURE 2 SECTION THROUGH SUNKEN PIPE SHOWING CANS CONTAINING DOSIMETERS

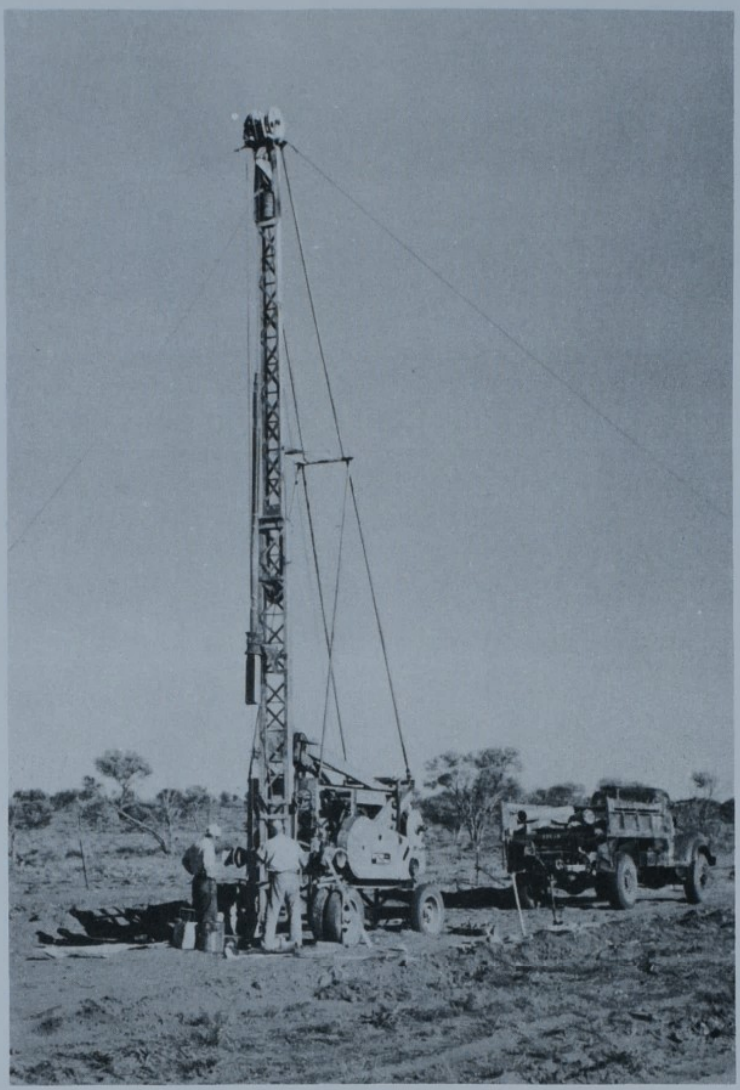

FIGURE 3. THE WELL-BORING MACHINE IN OPERATION

FIGURE 4. THE CONTENTS OF THE HOLE, AS THROWN OUT BY THE WELL-BORER. THE SPOIL WAS THROWN OUT AS A SLURRY OF APPROXIMATELY THE SAME CONSISTENCY AS FRESHLY-MIXED CONCRETE.

FIGURE 5. A CAN, FILLED WITH ITS DOSIMETERS AND SOIL, BEING LOWERED INTO A HOLE BY A "SHEPHERD'S CROOK".

FIGURE 6. A FILLED CAN, IN THIS CASE ONE WITH THE DOSIMETERS AT THE TOP, READY TO BE LOWERED INTO A HOLE.

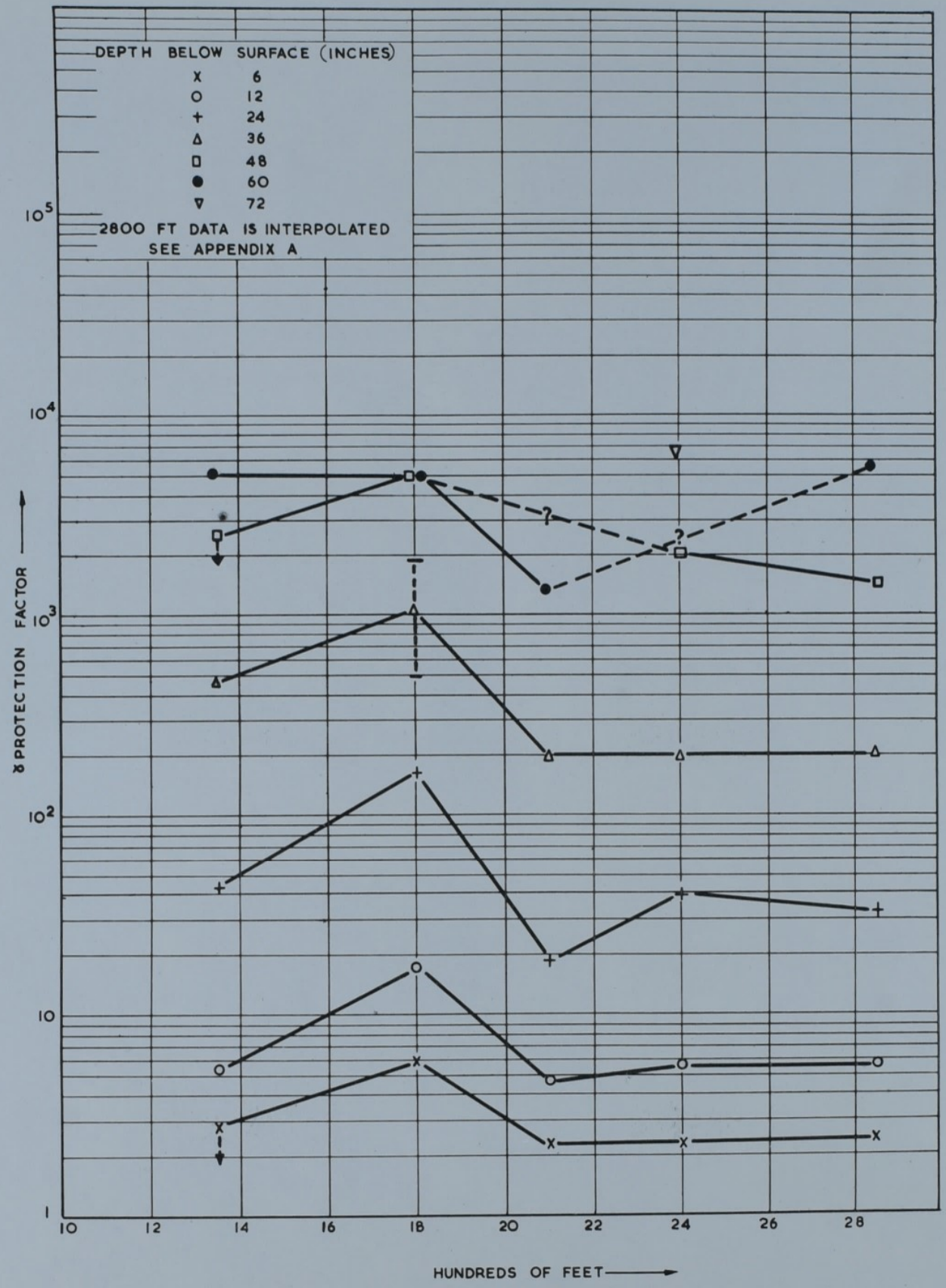

FIGURE 7a. ROUND 2 γ RADIATION PROTECTION FACTORS

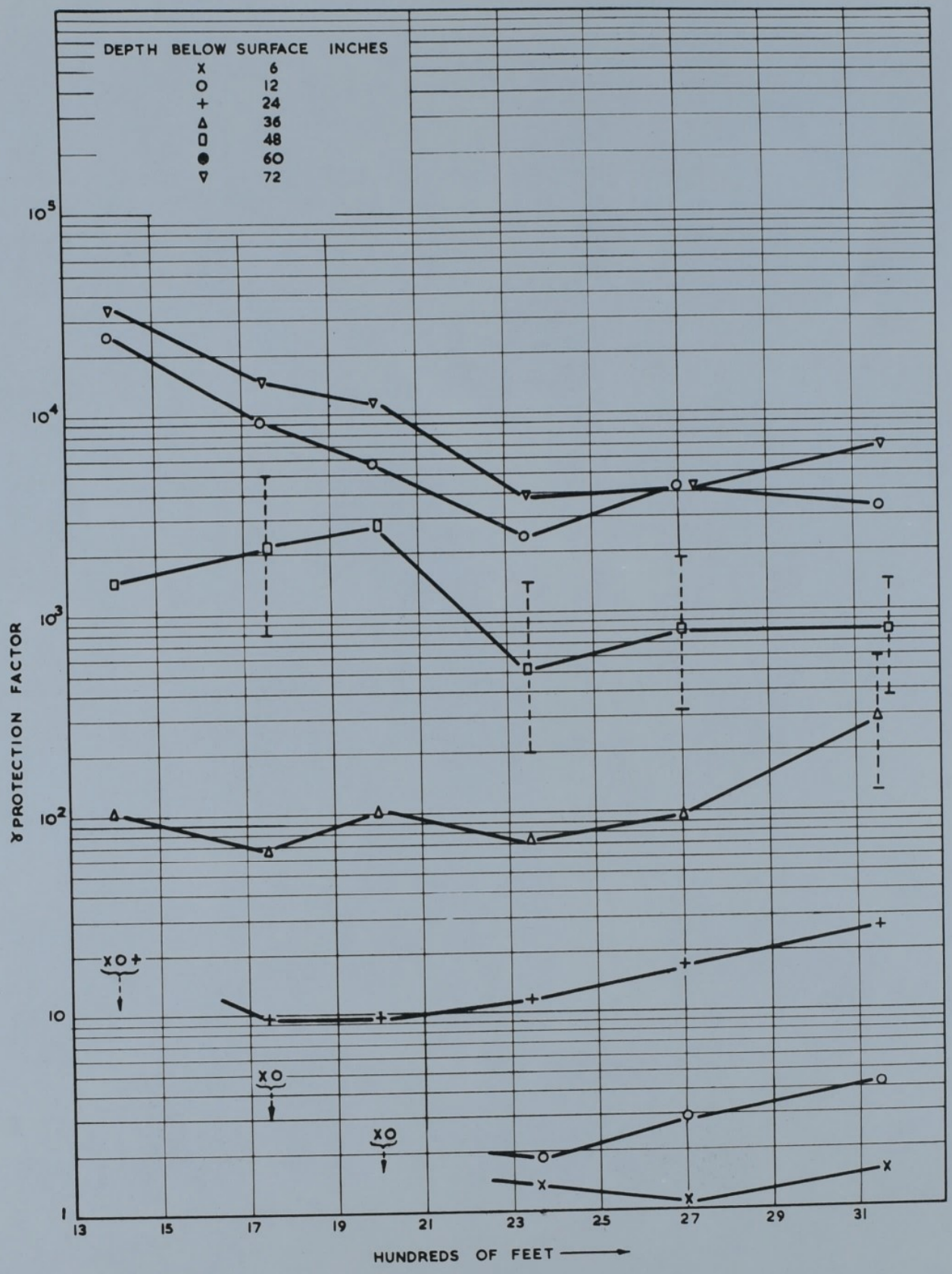

FIGURE 7b. ROUND 3 γ RADIATION PROTECTION FACTORS

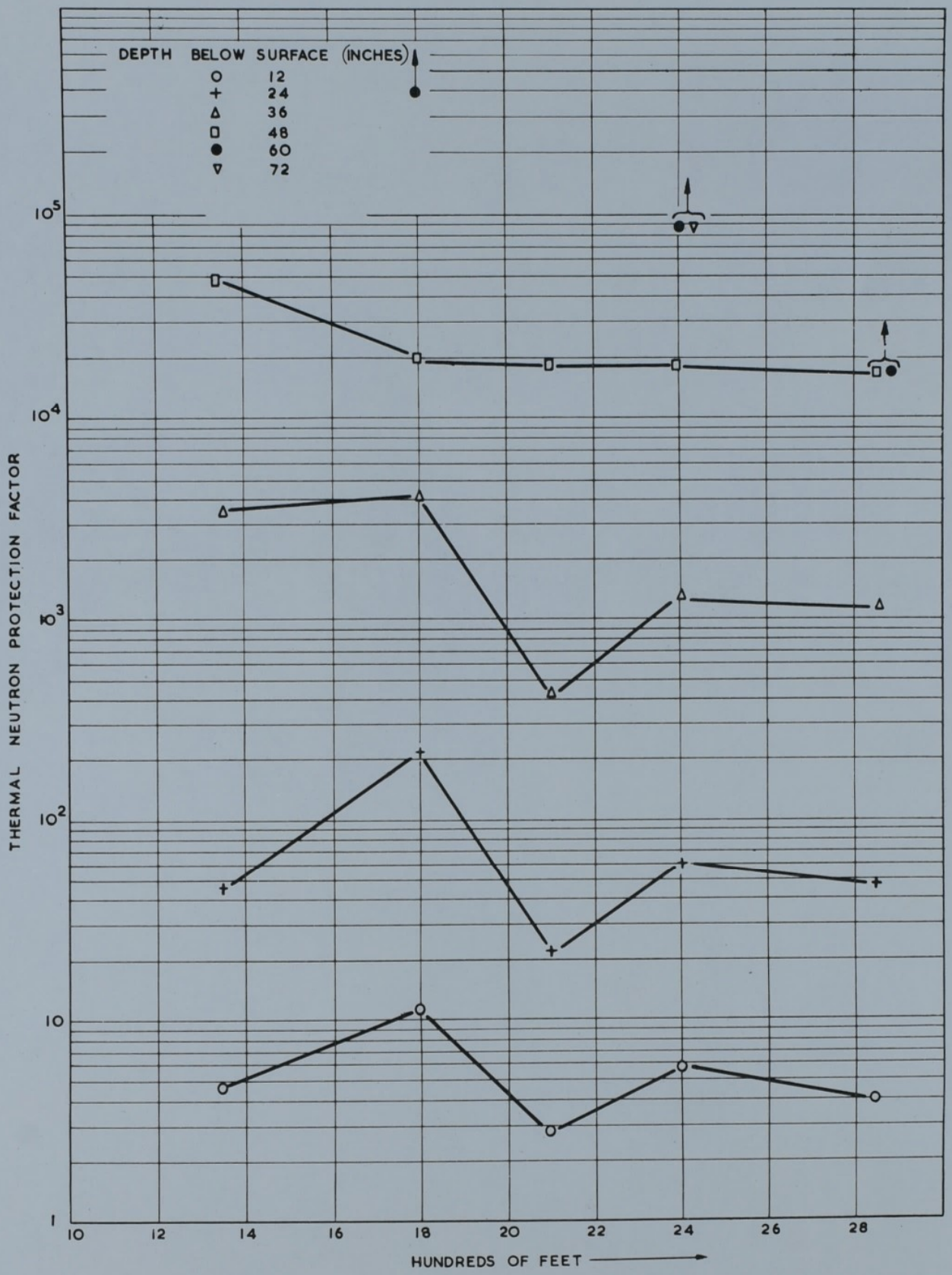

FIGURE 8a ROUND 2 THERMAL NEUTRON PROTECTION FACTORS

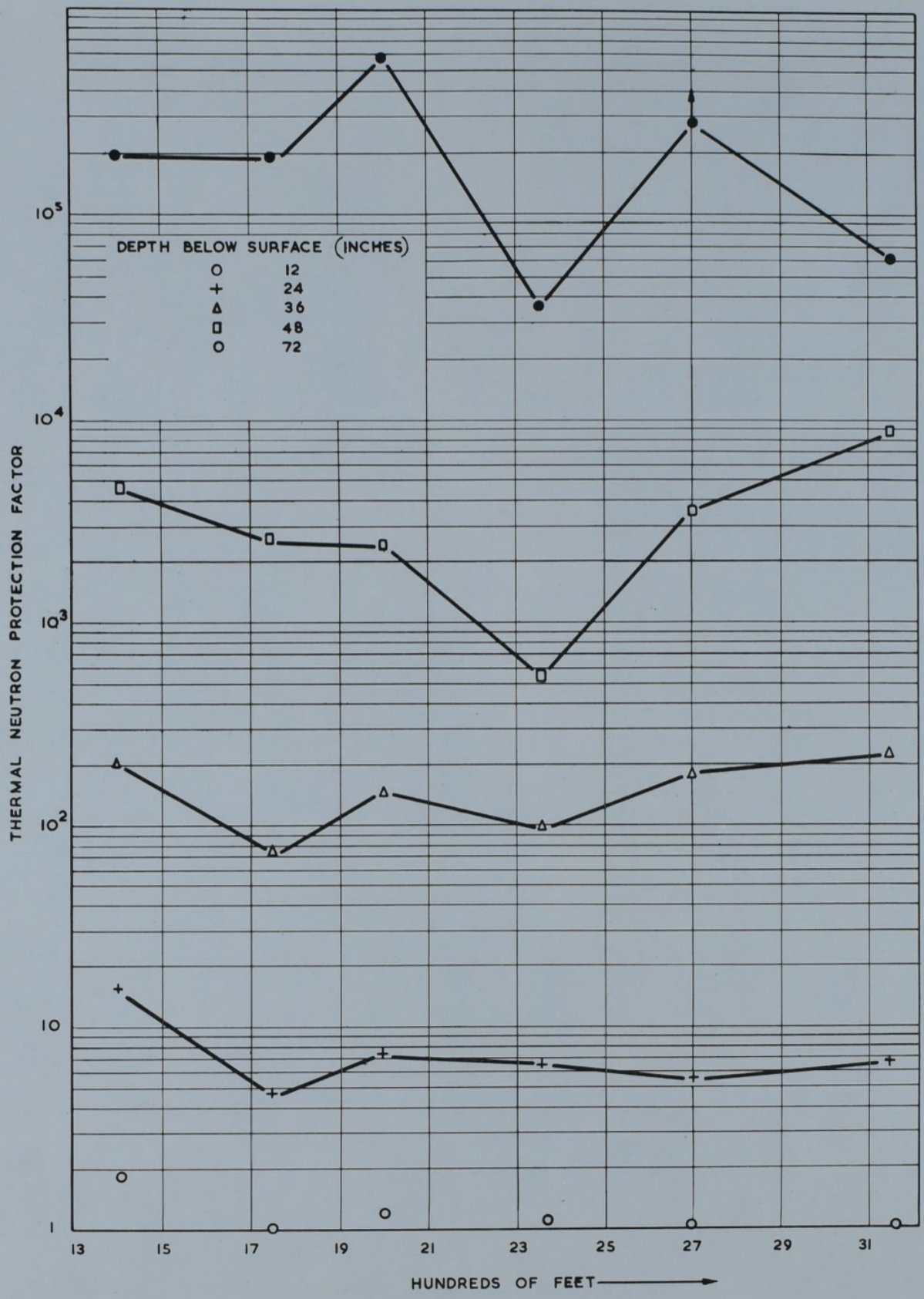

FIGURE 8b. ROUND 3 THERMAL NEUTRON PROTECTION FACTORS

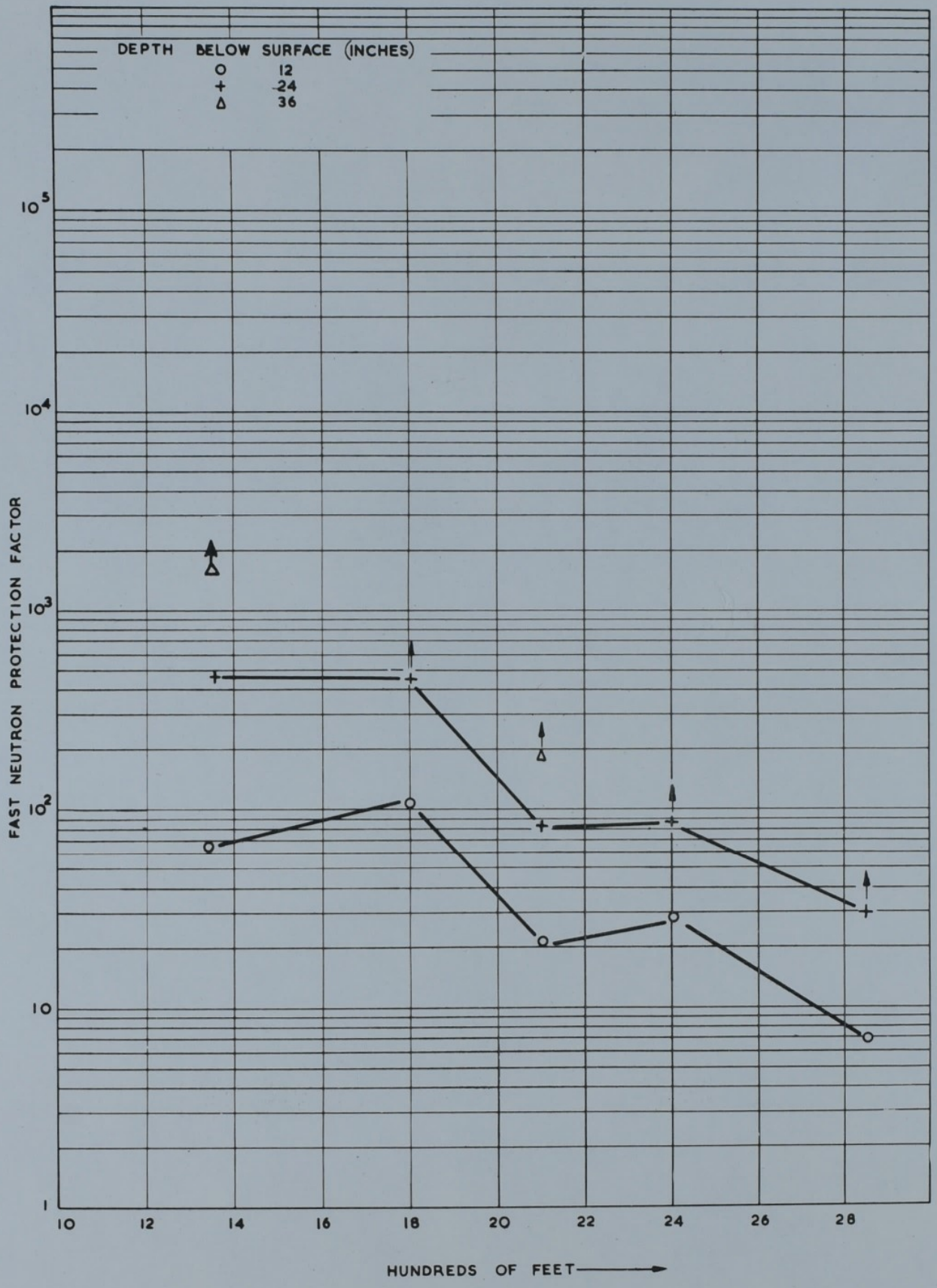

FIGURE 9a. ROUND 2 FAST NEUTRON PROTECTION FACTORS

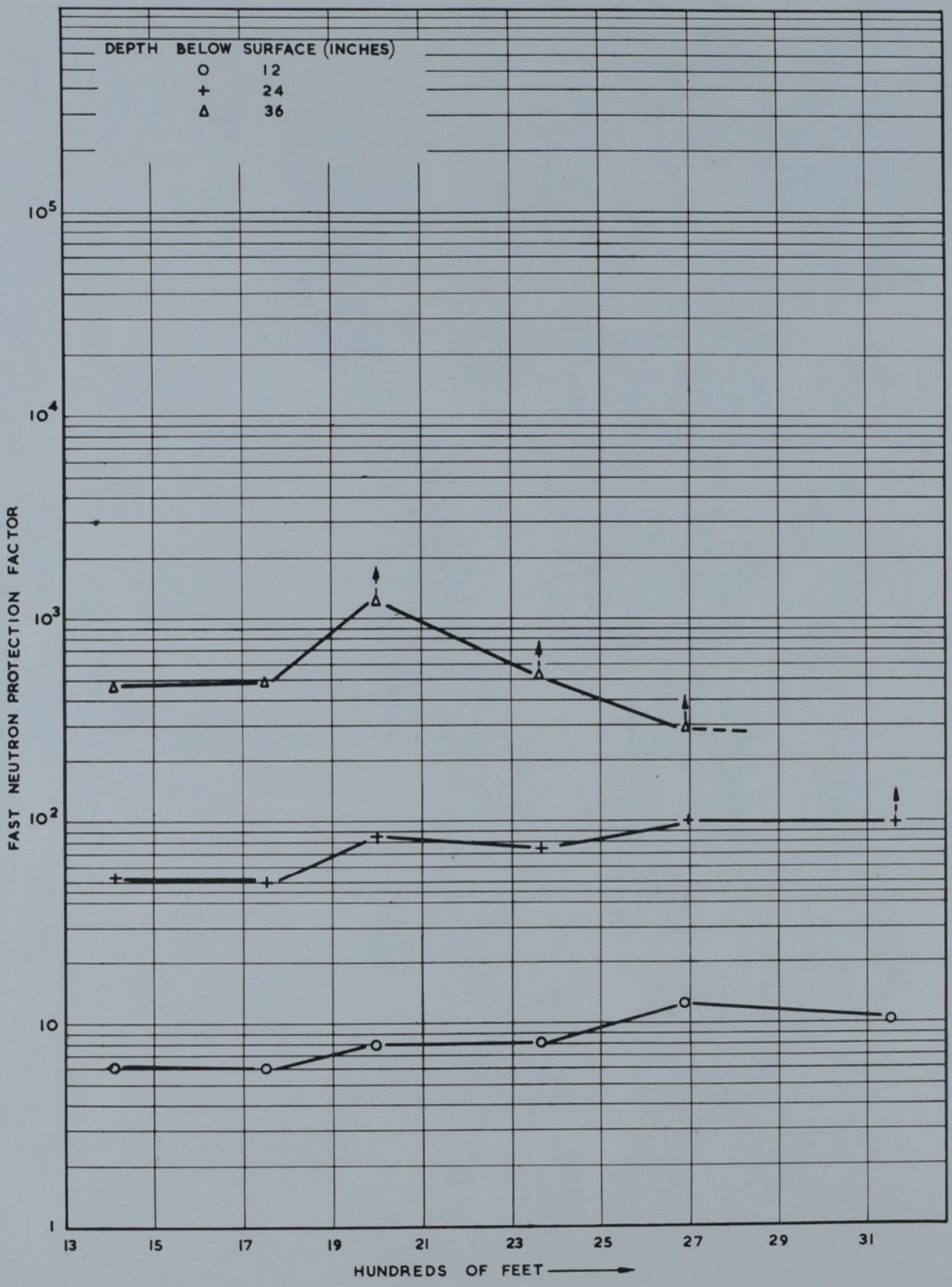

FIGURE 9b ROUND 3 FAST NEUTRON PROTECTION FACTORS

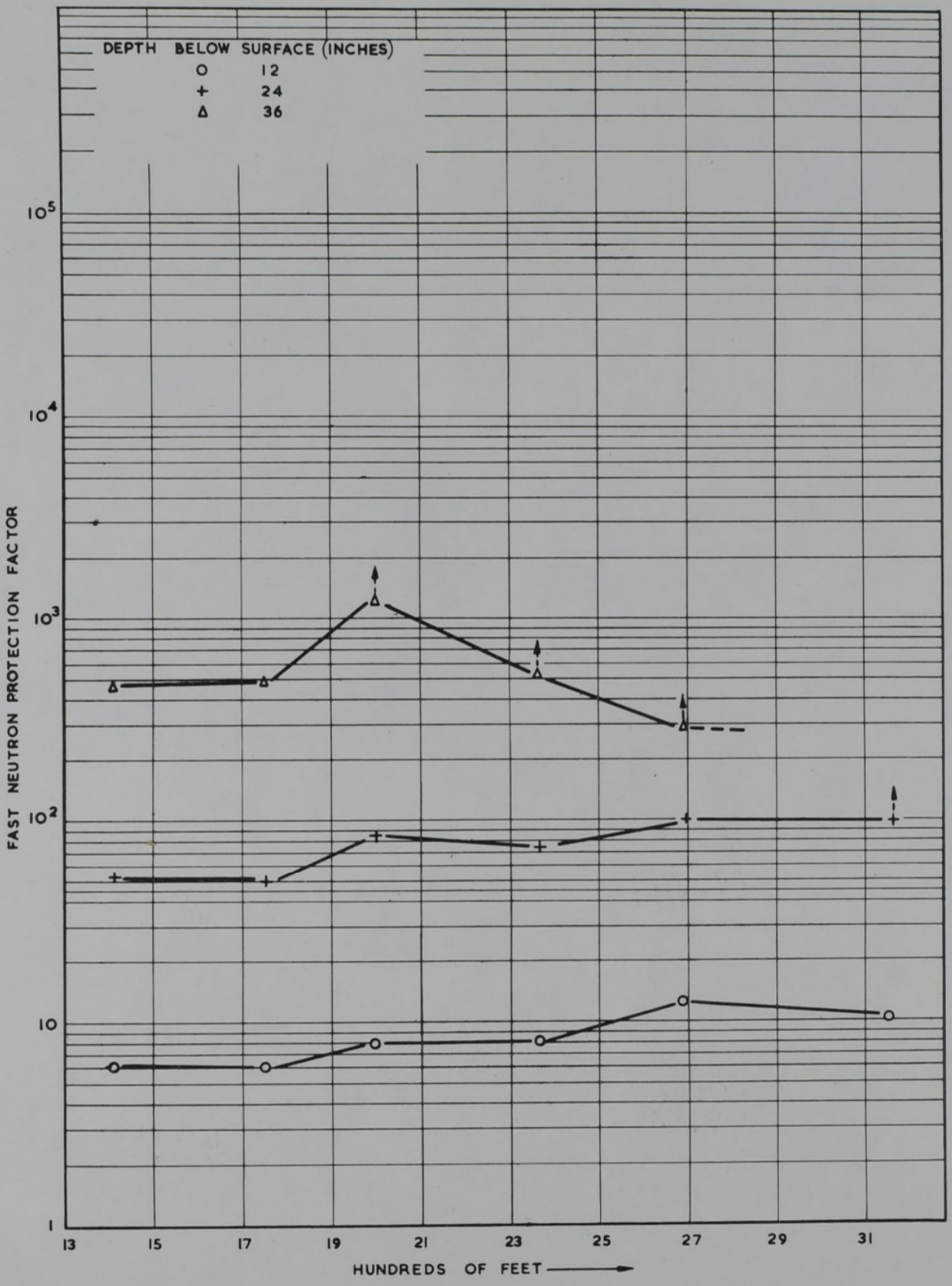

FIGURE 9b ROUND 3 FAST NEUTRON PROTECTION FACTORS

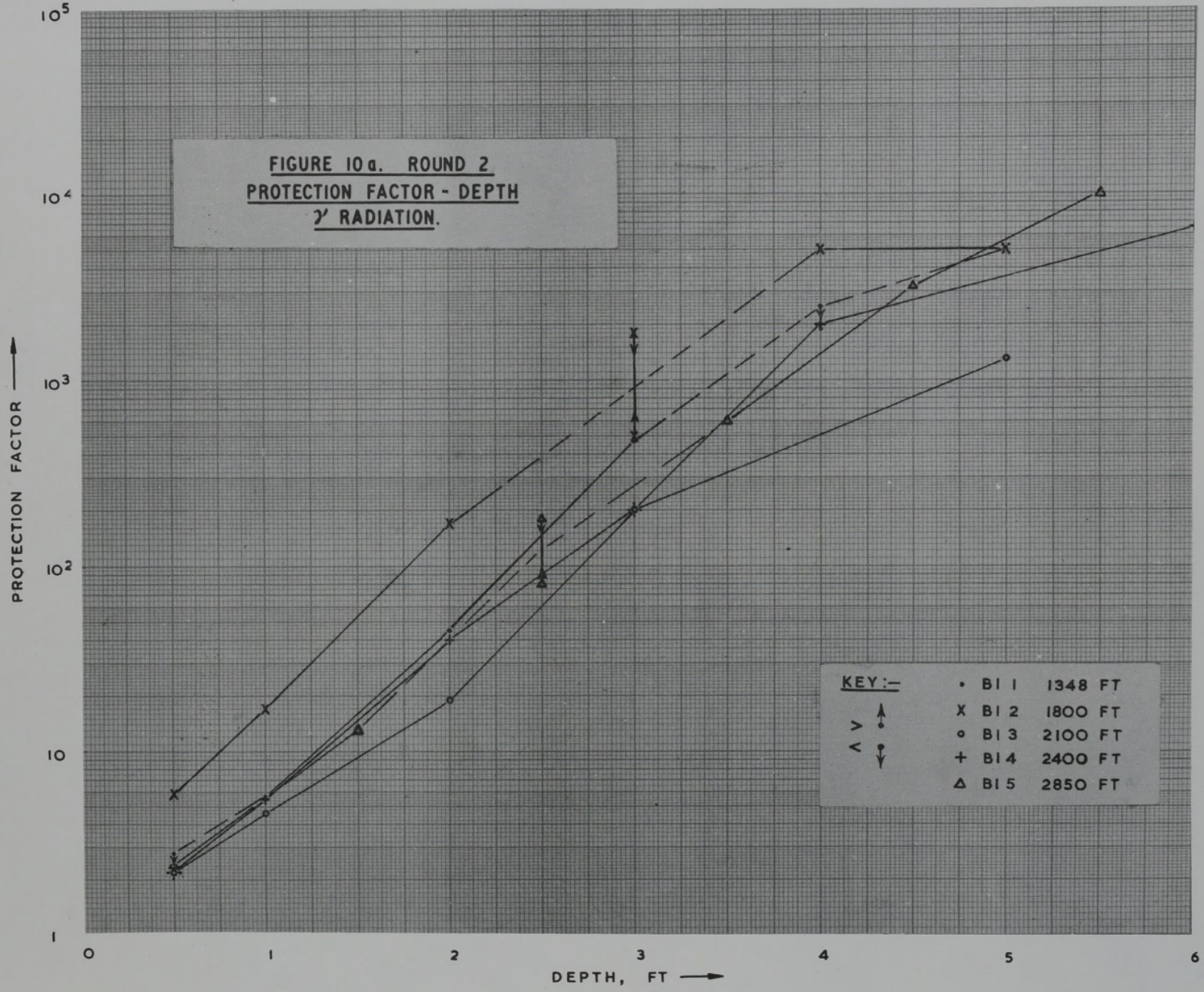
FIGURE 10a. ROUND 2
PROTECTION FACTOR - DEPTH
γ RADIATION.
PROTECTION FACTOR
DEPTH, FT
KEY:-
B1 1 1348 FT
B1 2 1800 FT
B1 3 2100 FT
B1 4 2400 FT
B1 5 2850 FT

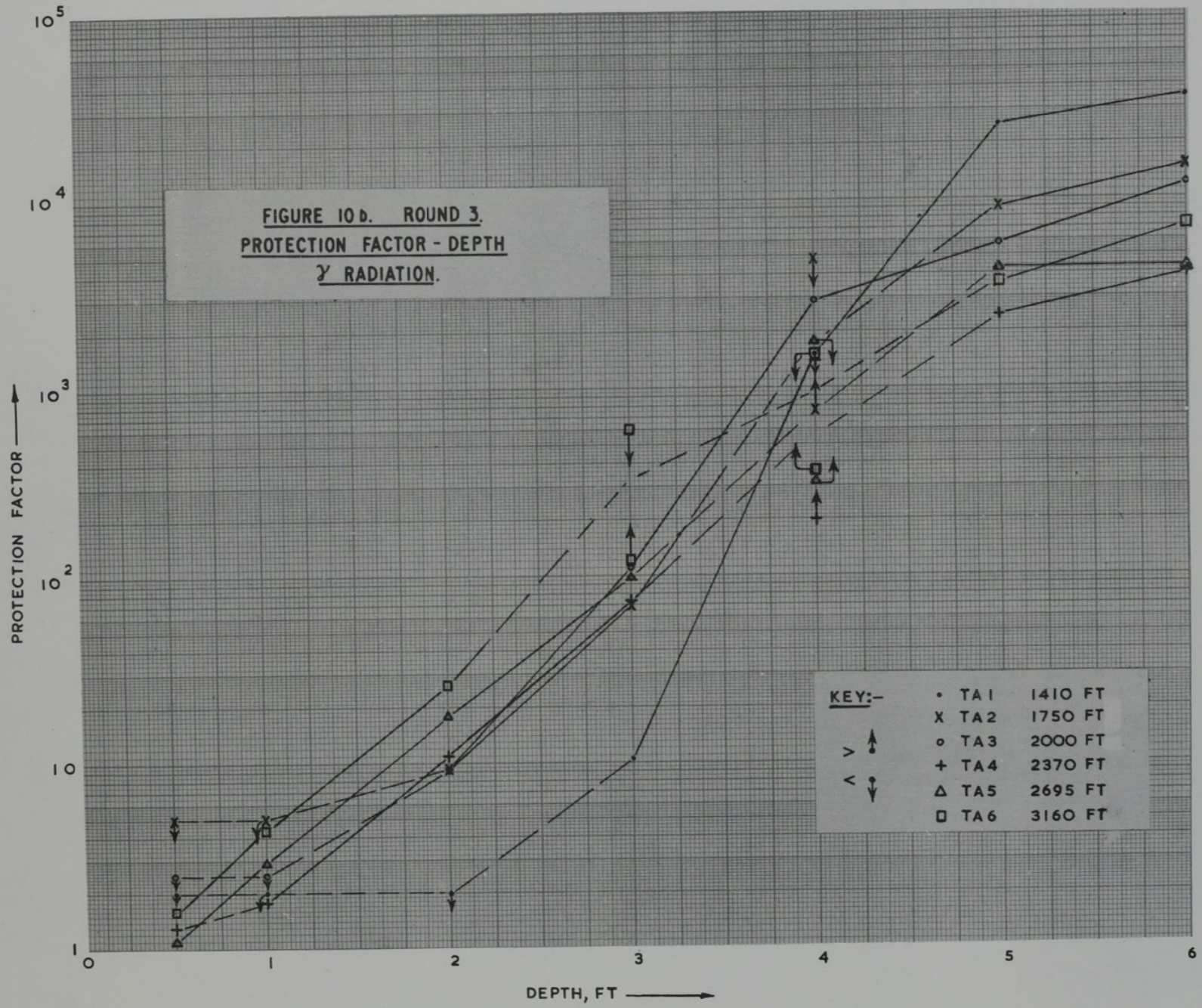
FIGURE 10 b. ROUND 3.
PROTECTION FACTOR - DEPTH
γ RADIATION.
PROTECTION FACTOR
DEPTH, FT
KEY:-
TA 1 1410 FT
TA 2 1750 FT
TA 3 2000 FT
TA 4 2370 FT
TA 5 2695 FT
TA 6 3160 FT

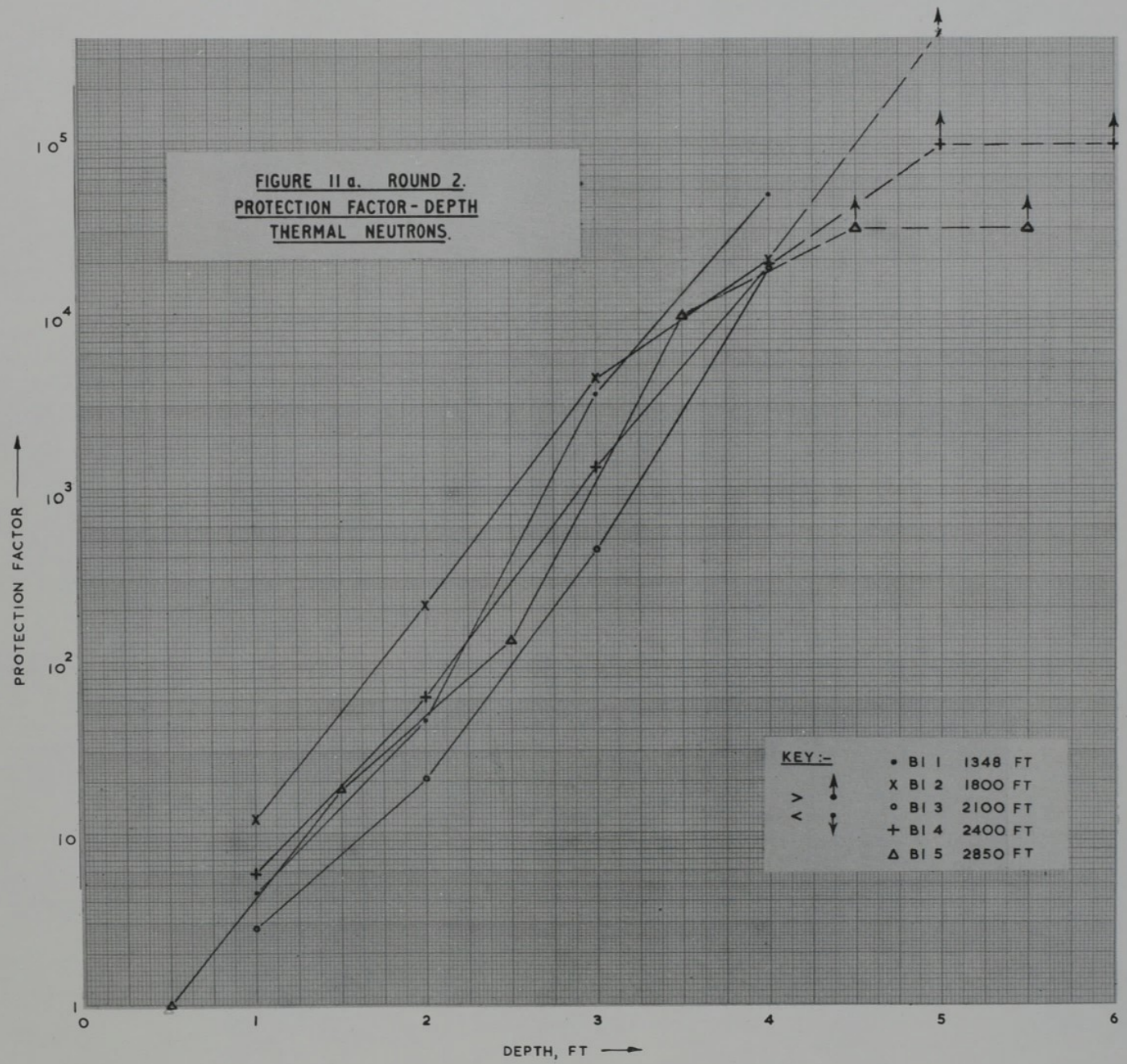
FIGURE 11 a. ROUND 2.
PROTECTION FACTOR - DEPTH
THERMAL NEUTRONS.
PROTECTION FACTOR
10^5
10^4
10^3
10^2
10
1
0
1
2
3
4
5
6
DEPTH, FT
KEY:-
BI 1 1348 FT
BI 2 1800 FT
BI 3 2100 FT
BI 4 2400 FT
BI 5 2850 FT

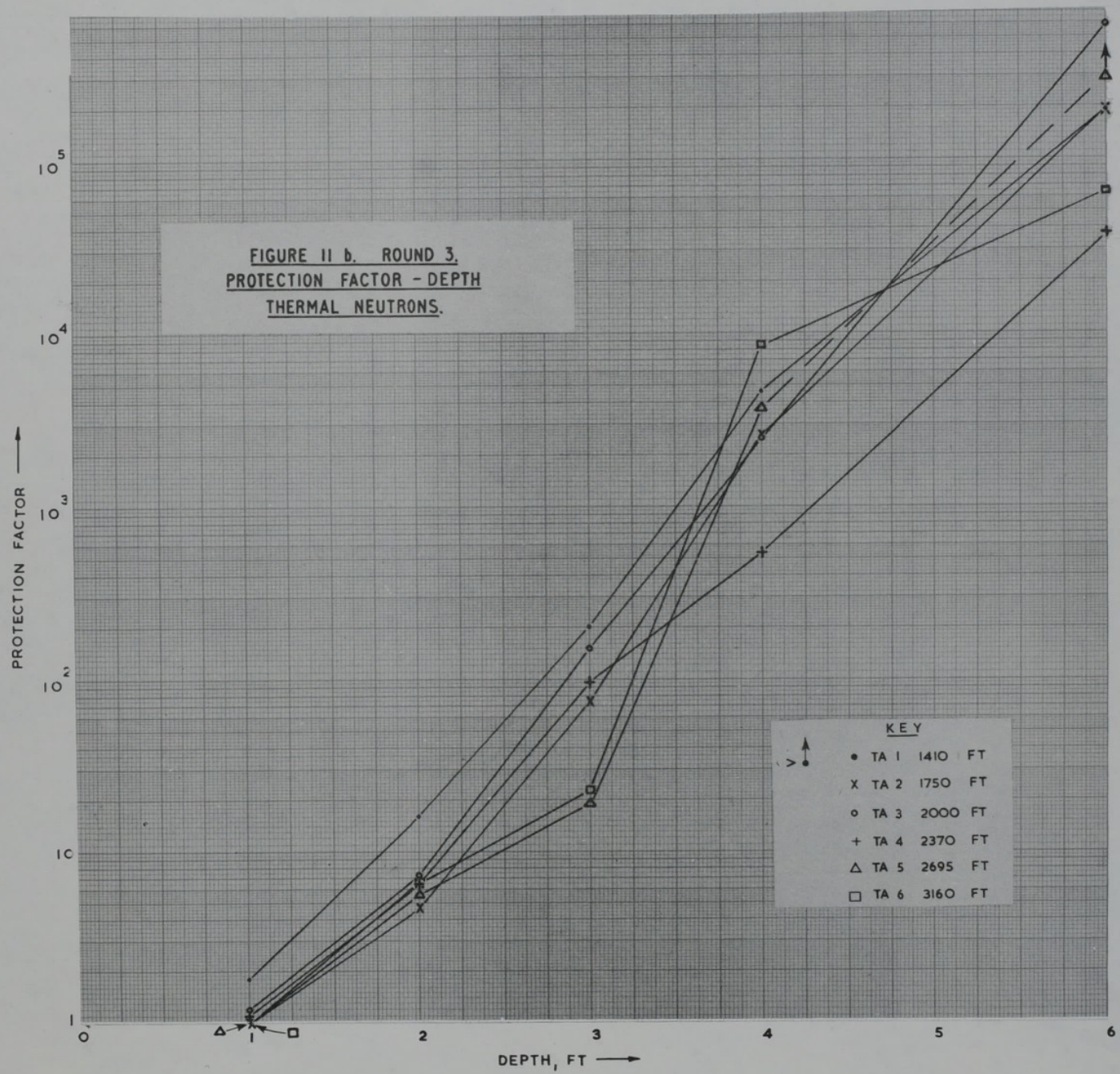
FIGURE 11 b. ROUND 3.
PROTECTION FACTOR - DEPTH
THERMAL NEUTRONS.
PROTECTION FACTOR
10^5
10^4
10^3
10^2
10
1
0
1
2
3
4
5
6
DEPTH, FT
KEY
TA 1 1410 FT
TA 2 1750 FT
TA 3 2000 FT
TA 4 2370 FT
TA 5 2695 FT
TA 6 3160 FT

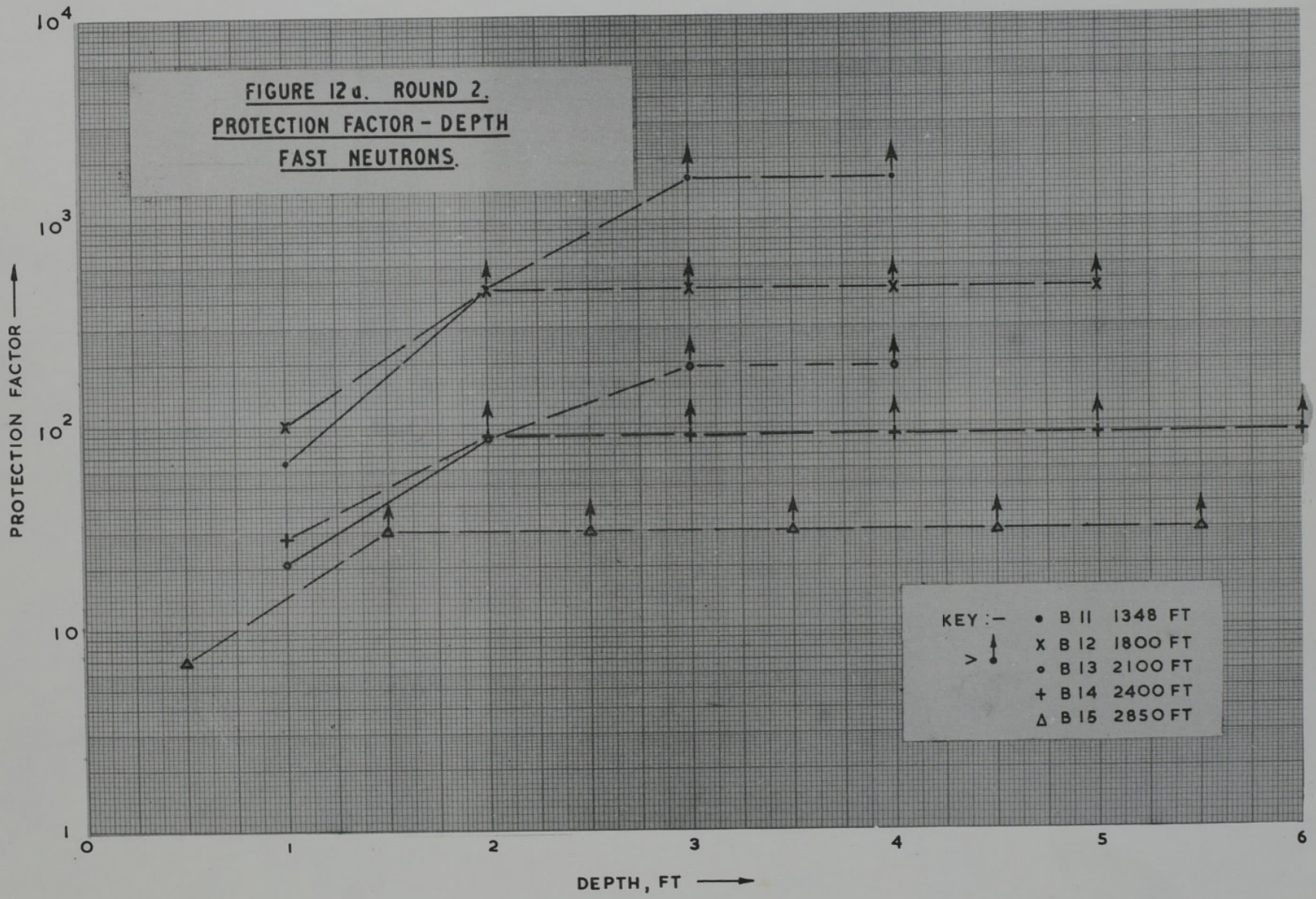
FIGURE 12a. ROUND 2.
PROTECTION FACTOR - DEPTH
FAST NEUTRONS.
PROTECTION FACTOR
10^4
10^3
10^2
10
1
0
1
2
3
4
5
6
DEPTH, FT
KEY :-
B 11 1348 FT
B 12 1800 FT
B 13 2100 FT
B 14 2400 FT
B 15 2850 FT

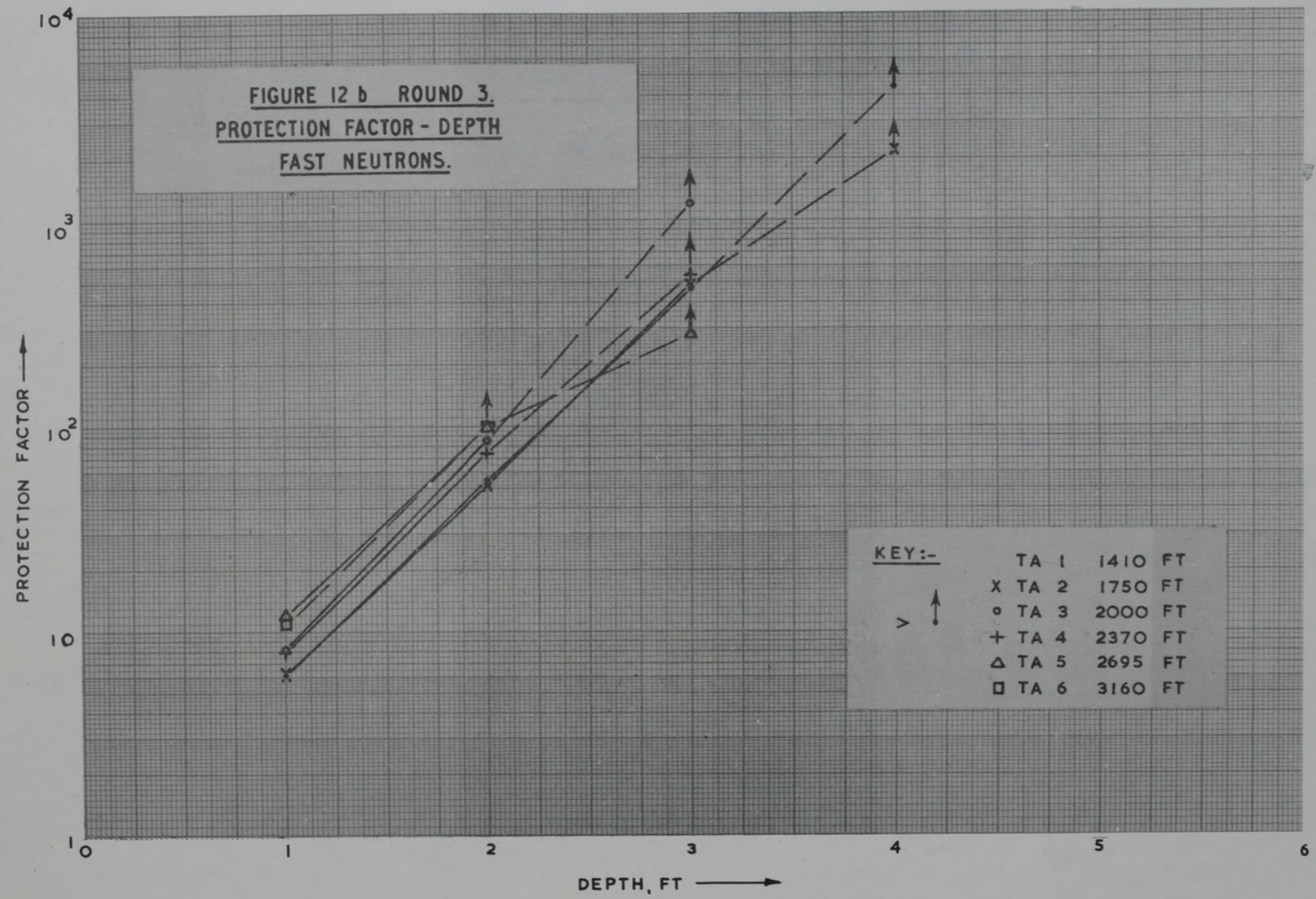
FIGURE 12 b ROUND 3.
PROTECTION FACTOR - DEPTH
FAST NEUTRONS.
PROTECTION FACTOR
DEPTH, FT
KEY:-
TA 1 1410 FT
X TA 2 1750 FT
o TA 3 2000 FT
+ TA 4 2370 FT
Δ TA 5 2695 FT
□ TA 6 3160 FT

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ATOMIC WEAPONS RESEARCH ESTABLISHMENT

AWRE REPORT No. T 10/60

On the Resuspension in the Atmosphere of Radioactive or Other Fine Particulate Material Deposited on the Ground

K. Stewart

A.W.R.E.,
Aldermaston, Berks.

November, 1960

~~CONFIDENTIAL DISCREET~~

United Kingdom Atomic Energy Authority

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On the Resuspension in the Atmosphere of Radioactive or Other Fine Particulate Material Deposited on the Ground

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1. INTRODUCTION

The possibility that the resuspension of deposited radioactivity could give rise to an inhalation hazard has long been recognised. On the early nuclear weapon trials, the radiological hazards from this source and from the γ radiation field were carefully determined. It was found on both the Hurricane and Totem trials that the potential hazard from the inhalation of resuspended fission product fallout was insignificant in comparison with that from the external γ radiation, and so measurements of the latter only were sufficient for health control surveillance purposes.

However, when the contamination is due to a long lived radioactive material which gives rise to no significant external radiation field, the inhalation hazard due to resuspension needs further consideration. The object of this paper is to examine the experimental evidence available and to deduce a representative value for the factor between the contamination level and the airborne activity.

2. EXPERIMENTAL EVIDENCE

The results of the experimental measurements of the airborne activity which were made on a number of field trials are summarised in Tables 1 and 2. The results obtained on the Hurricane [1], Totem [2] and Buffalo [3] series of nuclear tests are shown in Table 1. In addition the results obtained on two Civil Defence trials [4] and a brief summary of some health physics surveillance measurements [5] made during field experiments are also included. In all these experiments the air-

borne concentration above a contaminated area was measured and the relationship between the concentration and the level of contamination determined. This relationship is the resuspension factor, K, and is defined by

$$K\ (m^{-1}) = \frac{\text{Airborne Concentration (Curies } m^{-3})}{\text{Contamination Level (Curies } m^{-2})}.$$

On a US trial [6], which had as its object the study of the dispersal of plutonium (and uranium) from a simulated warhead as the result of detonation of the high explosive, measurements were made over an extended period. These results show that the airborne concentration is not independent of the contamination levels upwind. In experiments reported by Healy and Fuquay [7] a readily identifiable particulate material was employed as a contaminant on selected types of ground surface and the airborne concentrations downwind of the seeded areas were measured. From the results (see Table 2) a factor, F, is deduced, which is defined in the following way

$$\text{Particulate Material Airborne from Surface (particles/m}^2\text{/sec)} = \frac{F^{u^2}}{\rho\, d} \times \text{Particulate Contamination (Particles/m}^2\text{)},$$

where u is the wind speed in m/sec, ρ is the material density in g/cm^3 and d is the diameter of the particles in μ. From all these results it is quite clear that the amount of any ground deposited material which is resuspended in dust under differing conditions, is likely to be a very variable quantity. This conclusion would be expected on quite general considerations. Thus, the fineness of the soil or sand in the surface layer, the air turbulence and wind speed in the air layer close to the surface, the moisture in the ground and the presence of external sources of agitation (such as moving vehicles) will all affect the amount of material resuspended in the air. Further, the particle size distribution of the dust on which the radioactive or other deleterious material is deposited will be an important factor in determining the fraction of resuspended material which constitutes an inhalation hazard. The largest diameter of particle which is likely to reach the critical parts of the lung is about 10 μ; this diameter is less for high density materials, and for dusts generally is unlikely to exceed 6 μ. Because impaction is the more important mode of deposition in the respiratory system the particle size scales as $\rho^{-\frac{1}{2}}$. Fortunately, particle size measurements were made on some occasions.

2.1 Operation Hurricane

The results obtained in the fallout area on Hurricane form a self-consistent set, except for the two extreme values. The samples of airborne material were measured in terms of β activity, whereas the contamination level was determined by a γ radiation survey. The known relationship between the β and γ activity of fission products permits the results to be compared, although there may be some uncertainty in individual figures because the γ dose-rate depends on the area of contamination and the terrain. The results obtained at the same time for the amount of α activity resuspended are in close agreement with values estimated from known detail of the weapon and its performance. This firing occurred underwater and the fallout was mainly in a finely divided form. An average value of 1×10^{-5} m^{-1} was obtained for the resuspension factor K under conditions when the ground was disturbed mainly by wind and natural turbulence, but, there may have been some instrument recovery operations in progress.

It is noteworthy that, apart from decay, the fallout pattern, determined by γ survey was not markedly changed over a period of more than a year (405 days). The observed decay in the γ radiation dose-rate over the period from the time of the original surveys to the survey about a year later corresponds quite closely to that calculated for the fission products. Thus, even though there was some drifting of sand and the area of the survey was effectively much less because of decay, this result shows that only a small fraction could have been removed by the wind. This result is all the more significant since a cyclone and a total of 16 in. of rain are reported for the period. The uncertainties inherent in the measurements mean that it is not possible to estimate accurately the amount removed by weathering, but it is unlikely to be much greater than 10%.

2.2 Operation Totem

The results obtained on the Totem trials show that the problem was examined carefully at the time. One of the relevant differences between Hurricane and the later trials in the Australian desert is that for the latter the conditions were dry and a considerable fraction of the fallout was on, or in, material that had been fused. This may account for some of the very small values for the resuspension factor.

The results obtained at the back, and over the tailboard, of a Landrover vehicle in motion show that under these rather severe

conditions, the maximum value is only about 1×10^{-5}. Carter, in the report on the Totem measurements, points out that the activity measured depended on the position of the sampling device at the back of the Landrover. It is noteworthy that the two results obtained on D + 7 in which the orifice of the sampler projected just above the tailboard, are comparable with those obtained on D + 4. The wind conditions for the two days are not reported, but a difference in wind strength might well account for the different concentrations observed within the back of the Landrover on the two days.

The evidence that the bulk of the activity is not rapidly redistributed by natural disturbance, nor appreciably by actual stir-up of the surface, is shown by the observed γ dose-rate measurements for the two days. The differences in the γ dose-rates on D + 4 and D + 7 correspond to fission product decay, and do not suggest that a significant part of the airborne material raised by vehicles between D + 4 and D + 7, or by natural erosion over this period, was blown away. Measurements of the amount of airborne radioactivity at clean sites downwind from the active area produced by the first round showed that very little was transported any distance on dust.

Summarising, we note that three different survey operations on foot, without vehicles moving in the vicinity, lead to a mean resuspension factor of 3×10^{-7}, or if four of the total of 33 results are omitted, the value is about 1×10^{-7}. Whereas, in the dust cloud thrown up by a Landrover the mean value is about 1×10^{-5}. It must be pointed out here that the roads on the trials sites in the Australian desert were formed by grading the ground and the surface did not contain any binder such as bitumen. The dust clouds raised by vehicles were heavy and were only typical of such desert conditions. However, it cannot be assumed that the dusty nature of the terrain in the Australian desert necessarily produces severe conditions because it may be argued that the activity deposited initially on the surface soon becomes mixed in a considerable amount of loose sand and earth as the naturally stabilised surface is broken down. This might lead to only a small fraction of the activity being available for resuspension.

2.3 Operation Buffalo

The two results obtained on Buffalo are principally of interest because of the particle size measurements. The gross resuspension factors are similar to those obtained on Totem and the particle size measurements suggest that about 20% or less of the airborne material could constitute an inhalation hazard.

2.4 US Trial - Plutonium Contamination Due to a One Point Explosion

In this trial (in Spring, 1957) a warhead containing a representative amount of plutonium was placed on the ground and the H.E. initiated at a point underneath. The contaminated area was determined by analysis of some 4000 deposition samples. The study of the condition of the contaminated area forms a continuing project. From the analysis of carefully collected soil samples it is known that the bulk of the activity is in the top ½ in. of soil and measurements of the distribution in depth made initially at 6 months after firing and subsequently 18 months later gave similar results. About ½ in. of rain fell during the first 6 months and this may have determined the extent of the penetration into the soil. It has been estimated that only from 4 - 9% of the original contamination had been removed by erosion.

For the observations on resuspension three sites were chosen with contamination levels of 560, 40 and 2.6 μg Pu/m^2. The results obtained over a period of 133 days showed that the concentration of airborne material was variable, depending on wind direction and speed, but on the average showed a continual decrease with time which may be expressed as a half-life of about 37 days. This half-life would be expected to be characteristic of the terrain and meteorological conditions existing at the Nevada Test Site, and also shows that the fine particulate material exposed to natural erosion is steadily depleted or fixed. This is borne out by the fact that there is apparently no direct relationship between the contamination level at the sampling site and the activity in the sample, but rather a relationship with the extent of the contaminated area up-wind. During the experiments the wind blew across the heavily contaminated zone towards the areas of lower contamination for a large proportion of the time, which explains why a relatively high value was observed for the sample collected in the region of over 2.6 μg/m^2. This result is examined in more detail in the discussion.

2.5 Civil Defence Trials

The two experiments carried out at the Civil Defence School at Falfield, Gloucester, are also of considerable importance and were the first investigations of the problem. The dust was contaminated with known amounts of carrier free I-131. Both the atmospheric dust loading and the airborne activity were measured. The first experiment was carried out in a confined space, approximately 8 ft × 12 ft × 7 ft in

height in which a rescue worker has to work his way from front to rear in search of casualties, passing back some of the debris by hand and shovelling the rest. A resuspension factor of about 2×10^{-4} was measured and a total dust loading of 110 mg/m^3. In the second trial, a collapsed house was used in which rescue workers were trained in debris clearance in the open by hand during a systematic search for trapped casualties. The resuspension factor was 2×10^{-6} and the dust loading in the atmosphere about 10 mg/m^3. The dust used in these experiments was a brick and plaster dust from a bombed site in Bristol and was quite fine, with a median particle size of less than 1 μ. A portion of the dust was treated initially with the carrier free I-131 solution and this dust was then spread over the experimental area. The difference in operations and the distribution of activity in the bulk of the dust and debris during each experiment would account for the different ratios of airborne activity to dust loading. Both trials were carried out under dry conditions in May. These experiments are of interest as lending general support to the values obtained in other experiments. They are, however, not directly applicable to the general problem because of the conditions, the first being in an enclosed space and both being particularly dusty operations.

2.6 Health Physics Surveillance

The last set of results given in Table 1 was obtained during Health Physics control of clean-up operations in the firing zones after certain kinds of supplementary trials. The majority of the samples were obtained at a height of about 1 ft above the ground. Since the observed particle sizes are quite large, the fraction contributing to a possible inhalation hazard is small.

2.7 Trials with Small Areas Contaminated with an Identifiable Particulate Material

In two series of experiments reported by Healy and Fuquay [7], known amounts of particulate material were deposited on circular areas of different kinds of ground surfaces. The areas were quite small; 3 m radius in one series and 1.5 m in the other. The tracer material was a fluorescent particulate with a mass median diameter of 7 μ and a total size range of 1 - 35 μ. In the first series the concentration of airborne material due to natural erosion was measured at 40 m and 61 m downwind at a height of 0.5 m. The results are summarised in Table 2. Detail of how the samples were obtained and analysed is not given but it is stated that any depletion of the source

was neglected in the estimation of F. Both wind speed and particle size were taken into account in estimating F from the experimental results, and it was found that although the observed airborne concentrations were spread over a range of two decades, the values of F were sensibly constant (1.1 to 6.8×10^{-7}). Therefore, these results lend support to the hypothesis that the amount of material resuspended is proportional to μ^2. However, it should be noted that the wind speed was measured at a height of 2 m, whereas the relevant wind speed is that at the surface and hence the implication is that the wind profiles were similar at the time of each measurement. In the second series the effect of a short period of rain (about 2 hr) was observed. The results appear to be somewhat inconsistent, there being a reduction of about three in the value of F in the case of furrowed soil, whereas for grass it is greater than for dry conditions. The quoted average for the damp period is 0.6×10^{-7} and for the dry conditions 2×10^{-7}. These average values suggest an overall reduction by rain of about 3.

3. DISCUSSION

It was observed on both Hurricane and Totem that there was no significant shift of activity on the ground due to resuspension in the air and subsequent dispersal by the wind. A similar result was reported for the US trial and in this case the distribution in depth was also found to be constant over the period 6 months to 2 years after deposition. In all these cases the surface was largely undisturbed as the result of human activity, but there was continual natural erosion. From examination of these results it appears that the deposited material rapidly becomes mixed in the top few millimetres, perhaps centimetre, of soil or sand and a considerable part attached to coarse particles. There may remain up to about 10% which is near the surface and can, when once airborne, remain suspended for a considerable time to create at least a potential inhalation hazard. This material may be steadily spread over an ever wider area, which process would lead to the apparent half-life of about 37 days found in the case of the Nevada Test Site. A process of fixation to the coarser particulate material in the top surface layer would also account for the permanence of the contamination and the reduction of the fraction which can be resuspended. However, there does not appear to be any experimental evidence to support this idea, except in the case of cultivated soil. It is necessary, therefore, in any complete treatment of the problem, to take into account the change in the contamination pattern with time. Clearly, this is a very difficult problem and a complete solution is not attempted in this paper. Part of the difficulty lies in the lack of a proper understanding of the mechanisms which control the resuspension of surface material, particularly

the very fine particles which may constitute an inhalation hazard. The studies reported by Bagnold and by Chepil suggest that coarse material is first moved by the wind and the subsequent disturbances lead to the suspension of other material. It appears reasonable to assume that the amount of hazardous material which becomes airborne from any particular area of surface will be proportional to the amount of contaminant present, may be regarded as originating from a ground level source, and be considered in accordance with Sutton's theory for the travel of smoke clouds, provided allowance is made for re-deposition. If the surface contamination on particles of diameter d at time t and position x, y is given by S(s, y, t, d), then the rate at which material becomes airborne from an element of area (dx,dy) may be written as fSdxdy, where f is constant for a given set of meteorological conditions and surface structure. Healy and Fuquay have proposed a relationship for f of the form

$$f = F\frac{u^2}{\rho d}, \qquad \text{.....(1)}$$

where u is the wind speed, d the particle diameter, ρ the density of the material and F is a constant. This relationship for taking into account the effect of wind speed and particle size is a grossly over-simplified one and may not adequately represent the real situation. Chepil [8] has defined several particle size ranges for soil depending on the ease or otherwise with which they are eroded. Thus, particles in the size range 50 - 500 μ diameter are said to be highly erodible, whereas those smaller than 20 μ are non-erodible except at very high wind speeds Bagnold [9] has reported a similar situation in the relationships of dust and sand movement. Thus, in the absence of human, animal or vehicular traffic, the principal way in which the finely divided material can become airborne is by the process of saltation. In this the grains of sand or soil (mainly in the 50 - 500 μ size range) are set in motion by the wind and subsequently cause surface disturbances on impact. There appears to be a critical wind speed below which the surface remains undisturbed, but above which sand grains begin to move and build up the saltation process. Once this is established, both fine and coarse material will become airborne. The threshold velocity to move sand (200 μ diameter) is about 2.5 m/sec at 0.3 cm above the surface. Hence an alternative simple form for the relationship would be

$$f = F_1(u - u_t)^2, \qquad \text{.....(2)}$$

where u_t is the threshold wind speed for surface movement and F_1 incorporates the other properties of the surface. However, the data available are inadequate to test a relationship of this kind. In the following examination of the airborne concentration and rate of removal of activity, we shall examine the effects of particle size on the rates of removal and the deposition of the material. The marked variations in the amount of material resuspended may well reflect the changes in wind speed but, because the measurements of micrometeorological factors were inadequate, little analysis can be attempted.

It was observed on both Hurricane and Totem and on the US trial that there was no significant shift of activity due to resuspension in the air and subsequent dispersal by wind. It may be argued that at Totem this was due to the nature of the fallout, but on Hurricane the fallout was not in the form of fused granules and the natural dust was made up of sand and broken coral. In the case of the US trial in Nevada the soil was essentially fine particulate material. If the surface contamination level may be assumed to remain approximately constant, then it is possible to deduce the order of magnitude of the resuspension factor which will permit this to be realised. It will be assumed that the cross-wind dimension of the area is large so that the infinite line source theory of Sutton may be applied. If the contamination level is S $\mu c/m^2$, then the rate at which material, more precisely of a particular size, becomes airborne may be assumed to be A (=fS) $\mu c/m^2/sec$. The elemental area of unit cross-wind width and downwind length dx may be regarded as a line source dQ (=Adx) $\mu c/m^2/sec$). This particulate material will be assumed to possess a terminal velocity V_D if the particles are large enough, or a deposition velocity V_D if deposition is determined more by turbulence and impaction than by sedimentation. In both cases the rate of deposition, D, will be given by $V_D \chi(x,O)$, where $\chi(x,O)$ is the airborne concentration at range x and ground level ($z = \theta$). It has been shown by Chamberlain [10], in the case of a source at ground level, that if deposition is taken into account, the source strength Q appropriate to any range x is given by the relationship

$$Q_x \quad Q_o \exp -\left(\frac{4V_D x}{\pi^{1/2} nuC_z}\right)^{n/2}, \qquad \text{.....(3)}$$

where x is the range in metres, u is the wind speed in m/sec, C_z is the coefficient of eddy diffusion in $m^{1/6}$ and n is a constant determined by

the atmospheric stability with the value of 0.25 for "average" or zero temperature gradient conditions. Therefore the airborne concentrated at range x from the source dQ will be given by

$$dX(x,o) = \frac{2dQ \exp\left[-\frac{4V_D x^{n/2}}{\pi^{1/2} n u C_z}\right]}{\pi^{1/2} u C_z x^{1-n/2}}$$

$$= \frac{2A \exp\left[-\frac{4V_D x^{n/2}}{\pi^{1/2} n u C_z}\right] dx}{\pi^{1/2} u C_z x^{1-n/2}} .$$

On integration we obtain the result

$$\chi(x,o) = + \frac{A}{V_D} \left[e^{-Y}\right]_{x_1}^{x_2}, \qquad \ldots\ldots(4)$$

where $$Y = \frac{4V_D x^{n/2}}{\pi^{1/2} n u C_z}$$

and x_1 and x_2 are the upwind distances of the boundaries of the contaminated area from the position of interest x. If this position is within the contaminated area, then $x_2 = 0$. In this case

$$\chi(x,o) = \frac{A}{V_D} (1 - e^{-Y}). \qquad \ldots\ldots\ldots(5)$$

The rate of deposition will be $V_D \chi$ and as the rate of resuspension is A, the net loss from the surface at x is given by Ae^{-Y}. If this term is to be small the value of Y must be greater than 1. By inspection of equation (4) it is found that the terminal or deposition velocity is the most important variable. The range x is of minor importance because the term $x^{1/8}$ increases only slowly with x. For deposition by turbulence and impaction a reasonable value for V_D is 2 cm/sec and assuming a wind of 5 m/sec, a value for Cz of 0.12 and putting $x^{1/8} = 2$ the value of Y is found to be 0.6. Hence, for fine dust of this kind, 10 - 20 μ diameter, significant loss by dispersal downwind would be expected. For a terminal velocity of 20 cm/sec, corresponding to about 50 μ, the removal would be very slow. The resuspension factor, K, is given by

$$K = \frac{\chi(x,o)}{S} = \frac{f}{V_D}(1 - e^{-Y}), \qquad \ldots\ldots (6)$$

and the decrease of K (in terms of f) with increase of particle size because of loss by redeposition, is shown in the Table 3 for the values of Cz, u and x quoted above.

For the circumstances which have been specified, viz. a large area of contamination, initially uniform and a steady but slow travel of material and contamination in one direction, it is reasonable to assume that these steady state conditions imply an essentially uniform contamination level except in the vicinity of the upwind edge. However, this level will decrease with time and the rate of removal of activity will be given by

$$\frac{dS}{dt} = -fSe^{-Y},$$

on integration this leads to

$$S = S_o \exp(-fte^{-Y}), \qquad \ldots\ldots (7)$$

and the half-life, $t_{1/2}$, will be equal to $\frac{0.693}{fe^{-Y}}$.

Some estimates of half-life are given in Table 3. It is found for fine dust that if the resuspension factor K has the value 1×10^{-5}, the half-life of the deposit would be about a month. This is similar to the US experimental result. These results are also in agreement with the observations obtained on weapon trials in Australia. In those cases where a resuspension factor of about 1×10^{-5} was obtained but the activity remained in situ for considerable periods, a large fraction of the resuspended materials was probably on coarse particles of 50 μ and larger. The two measurements made on Buffalo, in which the particle size distributions were determined, support this conclusion.

So far the contamination has been assumed to be uniform, which is a condition unlikely to be met in practice. Indeed, in the active area formed on the US trial, the contamination levels were from about 2000 $\mu g/m^2$ down to 5 $\mu g/m^2$ for the closed contours and to much lower

levels in the area beyond. Resuspension studies were carried out in areas where the total surface contamination was 560, 40 and 2.6 $\mu g/m^2$, but this wide range of values was not reflected in the samples of airborne activity. The positions were, from the aspect of the prevailing wind, downwind of the most active area. The theory already developed can be applied to this situation, but for ease of calculation the contamination pattern has been much simplified. It is found that the fallout area may be idealised to one with a cross-wind dimension of 800 m and a downwind profile given by

$$2000 \exp - \frac{x}{400} \quad \mu g/m^2 \qquad (x \text{ in m}).$$

At a position distance P downwind of the upwind edge (or effective peak in contamination), the airborne concentration on the mid-line of the rectangular zone and at 5½ ft above ground level will be given by

$$\frac{4 \times 10^3 f}{\pi^{\frac{1}{2}} u C_z} \int_0^P e^{-\frac{x}{400}} \cdot e^{-\frac{4V_D x^{n/2}}{\pi^{\frac{1}{2}} n u C_z}} \cdot e^{-\frac{z^2}{c^2 x^{2-n}}} dx \qquad \ldots.(8)$$

where X = P - x. This expression is only true for a short time because, once the airborne transport of activity is established, the downwind profile will change. However, the main object of the calculation is to show that airborne concentration at any point is affected significantly by the extent and density of the upwind contaminated area. It is found that, as the extent of the contaminated area upwind increases, the fraction of the airborne material which comes from the area immediately upwind of the position of interest decreases. Thus, at 550 and 1000 m from the upwind edge about half the airborne material comes from the area within 10% of these ranges immediately upwind of the site. At 2000 m the fraction is only about 1/4. The results are summarised in Table 4. The ratio between the extreme levels of contamination is about 40 and in the airborne concentrations about 20. This is in general accord with the US observations although the observed ratios were 200 and 7 respectively. If the value for f which corresponds to a half-life of about 30 days (see Section 3) is introduced, it is possible to estimate the doses which would be inhaled in a day. These are of the same order as those observed experimentally on the US trial. The information avail-

able on the US trial is not sufficient to enable a detailed comparison to be made. The upwind ranges and contamination profile have been estimated from the contamination contours available.

The results reported by Healy and Fuquay show that the constant F in equation (1) has a value of about 2 to 3×10^{-7} for several surfaces, i.e., grass, ploughed (furrowed) land and rock. The wind speeds were in the range 1 - 10 m/sec so that, provided allowance was made for the mean size of particle collected during each experiment (the particle density will be constant), these results give considerable support to the concept that resuspension depends, approximately, at least on u^2. By combining equations (1) and (6) the relationship between K and F is found to be

$$K = \frac{Fu^2}{\rho d V_D} (1 - e^{-Y}).$$

The terminal velocity of a particle of diameter 7 μ and density 4 g/cm^3 (i.e., assuming the fluorescent material to be ZnS) is about 0.6 cm/sec and a deposition velocity of this order, or perhaps as high as 2 cm/sec, may be assumed to be reasonable. If $F = 2 \times 10^{-7}$, then K is found to be about 5×10^{-6} for a wind speed of 5 m/sec. Therefore, the results of Healy and Fuquay indicate that for a particulate material with a mass median size of 7 μ, the value of K would be in the range 10^{-5} to 10^{-6} for quite a wide range of surface and meteorological conditions. Of this material, only that fraction in the size range smaller than about 7 μ would constitute an inhalation hazard.

4. CONCLUSIONS

As would be expected from elementary considerations it has been found that the airborne concentration at any position depends on both the extent and the intensity of the contaminated area upwind. The experimental results obtained on the US trial in which plutonium was dispersed and the theoretical estimates in this report both indicate that the extent of the upwind area is rather more important than an isolated area contaminated to a relatively high level unless this is immediately upwind of the sampling position.

As it is found that the actual samples of airborne activity show quite marked variability due mainly to variation in the wind and surface conditions, it is not unreasonable to argue that a simple resuspension factor taken in conjunction with a representative value for the contamination level for a particular area can provide a useful indication of the

degree of hazard regardless of the wind. The representative value for the contamination level would be an average figure taking into account the direction of the prevailing wind and extent and nature of the contaminated area.

From the experimental results examined it appears that a resuspension factor as large as 10^{-5} is likely to be appropriate under certain conditions. In particular it would be appropriate to dry dusty terrain where erosion occurs to some degree and to situations where there is vehicle movement on dry dusty roads. Higher values, namely, 10^{-4} to 10^{-3}, have been observed under rather special conditions at some trials, but consideration of the rate of removal of activity suggests that for fine dust such a degree of resuspension would lead to widespread dispersal of the contaminant in a few days so that such high values could not persist. Under other circumstances values as low as 10^{-7} have been observed. The results reported by Healy and Fuquay suggest that a brief period of rain may reduce the amount resuspended by a factor of about 3. Under continuously damp conditions, such as are common in the UK, it is to be expected that the reduction would be rather greater, perhaps to a value of 10^{-6}. In any case the crude theory developed shows that if a resuspension factor of 10^{-5} applies to fine dust, up to about 20 μ diameter, this material is likely to be continually removed by the wind and the effective half-life of the erodible material would be of the order of 1 month. If the material is coarser than 20 μ, resuspension to this degree may take place; but little, if any depletion of the source will occur and neither will an inhalation risk exist. Therefore, provided the material resuspended from the ground surface is not predominantly in the hazardous size range ($< 6\,\mu$ diameter) the value for K of 10^{-6} would provide a conservative estimate of the inhalation hazard.

The observed reduction in effective contamination level by weathering is of considerable importance. Movement in such an area may bring contaminated material to the surface and, in effect, tend to offset this reduction.

The experimental evidence is far from comprehensive and observations under a variety of conditions have yet to be made. From the simple analysis attempted in this paper it is clear that the circumstances of each experiment must be accurately recorded in detail. The mechanism by which the fine particulate material is raised from the surface is of particular importance. The wind profile and the vertical turbulence, as functions of height above and near to the surface, may be expected to be significant variables to measure in this respect.

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TABLE 1

Summary of Experimental Results on Resuspension of Activity in the Air

Trial	General Circumstances of Measurement	Resuspension Factor	
		Range	Mean
Hurricane	Sample of airborne material obtained without artificial disturbance of ground surface (12 results)	1×10^{-6} to 8×10^{-5} but 10 values lie between values 0.47×10^{-5} to 1.6×10^{-5}	1×10^{-5}
Totem	Random samples collected in region of T1 crater in absence of artificial disturbance of the ground (9 results)	1×10^{-6} to 1×10^{-8}	2×10^{-7} (0.8×10^{-7} if one result at 1×10^{-6} excluded)
	Surveys on C and D roads of grid - no artificial disturbance of ground surface (14 results, with 6 indefinite but measured values all $< 2 \times 10^{-7}$)	1.5×10^{-6} to 1×10^{-8}	2.5×10^{-7} (or 0.8×10^{-7} if one result at 1.5×10^{-6} is excluded)
	Surveys on "Dingo" road - samples collected at back of Landrover in motion (21 results, 10 of which 2 were obtained over the tailboard) on the 4th and 7th days after the first test	On 4th day: 0.8×10^{-6} to 3×10^{-5} On 7th day: 0.6×10^{-6} to 4×10^{-6} On 7th day: 1.6 and 3.1×10^{-5} at tailboard position	1.4×10^{-5} 1.5×10^{-6} 2×10^{-5} at tailboard
	Survey of road to Site C (10 results) on 1st and 2nd days after the second test. Of these, 3 are indeterminate but less than 2×10^{-8} and only 2 are $> 1 \times 10^{-6}$	1×10^{-8} to 2×10^{-6}	4×10^{-7}
Buffalo	Sample collected during an instrument recovery sortie in which the sampler, a cascade impactor, was carried in the driving compartment of a Landrover for part of the time and was outside the stationary vehicle near the working party for the remainder		
	Round 1 (H + 18 hr)	2.5×10^{-5} but only about 10% of the activity was present on particles $< 6\ \mu$ diameter	
	Round 2 (H + 5 hr)	6.4×10^{-5} but only about 20% of the activity was present on particles $< 6\ \mu$ diameter	
Civil Defence Trial at Falfield	Representative brick/plaster dust sample contaminated with I-131 and distributed on greater amount of dust and used during two realistic Civil Defence, bomb-site, recovery trials.		
	1. Enclosed Space		2×10^{-4}
	2. Open Area		2×10^{-6}
Some representative results obtained during Health Physics surveillance of minor experimental trials at Maralinga	1. Uranium (1957) sample collected immediately downwind of crater at: 1 ft above ground 2 ft above ground 1 ft above ground (dust stirred up)		3×10^{-4} 1×10^{-5} 1×10^{-8} — Estimated that < 5% in hazardous size range
	2. Plutonium (1959 Vixen) sample collected at: 1 ft above ground: - dust created by vehicles - dust created by pedestrian	3×10^{-4}, 7×10^{-4} 1.5×10^{-6}, 3×10^{-4}	Particle size mainly 20 - 60 μ; estimated that < 1% in hazardous size range

Notes: 1. By hazardous size range is meant particles ≤ 10 μ diameter at unit density. For sand the corresponding size is about 6 μ and for PuO_2 about 3 μ.

2. Particles collected on the first stage of a cascade impactor are sized by direct examination under a microscope.

TABLE 2

Values Observed for F for Two Ranges and Different Wind Speeds

Distance, m	Airborne Concentration, X particles/m^3	Wind Speed, m/sec	Factor, F $\times 10^7$
40	86	2.7	3.7
	120	3.1	4.3
	28	2.7	1.9
	14	0.9	4.7
	4.6	1.8	1.1
	20	1.8	4.9
	1.4	1.3	6.8
61	9.2	2.7	2.7
	17	2.7	5.1
	16	2.7	5.8
	7.8	2.2	3.6
	1.4	3.6	3.6
	3.2	1.8	2.3
	6.4	1.3	6.8
			Mean 4.1

Notes:

1. In evaluating F the units used were ρ in g/cm^3 and particle diameters in μ.

2. It was assumed that n = 0.25 and Cz, Cy = 0.18 for the calculation of X from a relationship similar to equation (4).

TABLE 3

Estimation of Half-Life of Source of
Material for Re-Suspension

Type of Particulate Material	Terminal or Deposition Velocity, m/sec	K, m^{-1}	Estimated Half-Life for Contaminated Zone (days) for:		
			K 1×10^{-4}	K 1×10^{-5}	K 1×10^{-6}
Very fine dust)	0.001	30 f	2.5	25	250
diameter $\leq 1\ \mu$)	0.002	30 f	2.6	26	260
Fine dust up)	0.01	26 f	2.9	29	290
to about 20 μ)	0.02	23 f	3.4	34	340
Coarse dust,)	0.1	10 f	16	160	1600
fine sand ~ 50μ)	0.2	5 f	160	1600	16,000

TABLE 4

Theoretical Estimation of Airborne Concentration
Downwind of a Heavily Contaminated Area

Contamination at Point P, $\mu g/m^2$	Integral Term in Equation (8)	Airborne Concentration, $\mu g/m^3$	Dose Inhaled in 1 Day ($f = 3 \times 10^{-6}$)
500	3.57×10^{-2}	65 f	4.7×10^{-3}
160	1.36×10^{-2}	25 f	1.8×10^{-3}
13	1.6×10^{-3}	1.9 f	2.1×10^{-4}

Initial Distribution

Internal

No.	1	DAWRE, Dr. N. Levin
	2	DDAWRE, Mr. E. F. Newley
	3	HSC, Mr. R. Pilgrim
	4	GMO, Dr. J. B. Lynch
	5	SSCTD, Mr. P. A. White
	6	SSFE, Dr. J. A. T. Dawson
	7	SSGS, Mr. D. E. Barnes
	8	TA/DDAWRE, Mr. J. T. Tomblin
	9	AHSC, Dr. K. Stewart
	10	SRI, Mr. N. Pearce
	11	Mr. R. F. Carter, SRI
	12	Mr. J. Hole, SSGS
	13	Mr. W. N. Saxby, SSGS
	14	Mr. D. M. C. Thomas, SRI

External

AERE, Harwell

No.	15	Mr. A. C. Chamberlain
	16	Mr. N. G. Stewart

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	17	Mr. F. R. Farmer
	18	Dr. A. S. MacLean
	19	Dr. W. G. Marley

Medical Research Council

	20	Dr. J. L. Loutit
	21	Dr. E. E. Pochin

Ministry of Defence

	22	Dr. R. Press

CEGB

	23	Mr. C. A. Adams
	24	Mr. G. C. Dale